Agriculture Automation and Control

Yong He · Pengcheng Nie
Qin Zhang · Fei Liu *Editors*

Agricultural Internet of Things

Technologies and Applications

Springer

Agriculture Automation and Control

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The ultimate goal of agricultural research and technology development is to help farmers produce sufficient foods, feeds, fibers, or biofuels while at the same time, minimize the environmental impacts caused by these large scale activities. Automation offers a potential means by which improved productivity, resource optimization, and worker health and safety, can be accomplished. Although research on agricultural automation can be found in the published literature, there lacks a curated source of reference that is devoted to the unique characteristics of the agricultural system. This book series aims to fill the gap by bringing together scientists, engineers, and others working in these areas, and from around the world, to share their success stories and challenges. Individual book volume will have a focused theme and will be guest-edited by researchers/scientists renowned for their work within the respective sub-discipline.

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Preface

Growing world population, limited arable land, declining water resources, and increasing climate instability all together boost the demand for capable technologies to improve productivity and sustainability in agricultural production. The Internet of things (IoT) is one such technology. Compared to the traditional way of managing agricultural production, the IoT technology offers an integrated solution to allow farmers automatically monitor their productions using different types of sensing devices connected using the Internet to support their more effective management for achieving efficiency. Motivated by its high potential to enable farmers achieve productive and sustainable production, both the academy and relevant industries all over the world have put great efforts in developing usable IoT technologies for farmers.

A team led by Prof. Yong He, one of the pioneers in agricultural IoT research and the lead editor of this book, has developed, implemented, and demonstrated many agricultural IoT systems of different scales, from greenhouse control to regional field crop monitoring, and various applications, such as orchard management and aquaculture automation, in the past 10 plus years. All contributing authors have accumulated rich knowledge and experiences in developing and implementing this promising technology for different agricultural applications. This book compiles such knowledge and experiences by providing a comprehensive technology overview in a systematic way from three different angles, which are IoT fundamentals, information perception, and IoT applications. Chapters 1, 2, and 3 provide an overview of IoT technologies and some special issues involved in agricultural applications. Regarding the aspects of information perception, this book provides a comprehensive overview on sensing technologies for acquiring production-related information from soil, crop, farmland, livestock, and aquaculture environments (Chaps. 4, 5, 6, and 7). The acquirable information includes, but not limited to, soil nutrients, soil physical and chemical properties, crop nutrition, physiology, disease, and other stresses. In the applications group, it could be categorized into two subgroups of information processing: decision-making support (Chaps. 8 and 9) and field applications (Chaps. 10, 11, 12, and 13). The information processing subgroup introduced how the obtained information be processed to make it useable in supporting decision making for productive and sustainable agricultural production. The field applications subgroup introduced some special issues and requirements for different applications, from field crop and orchard management, greenhouse or plant factory automation, livestock or aquaculture facility control to the traceability of agricultural products. As a summary, this book has also brought in a research frontier of integrating big data and cloud computing into agricultural IoT to dramatically improve the information processing and intelligent decision-assisting capability for supporting more effective and profitable agricultural productions as its final chapter (Chap. 14).

It is also worth pointing out that the development of agricultural IoT, as an integrated novel agricultural technology, requires a transdisciplinary effort to seamlessly integrate the fundamental IoT technology, applications engineering, and agricultural domain knowledge into one system. As both the lead editor and almost all contributing authors are experts in applications engineering, this book may unavoidably present the knowledge more from the applications system engineering point of view. For readers interested in learning more about fundamental theories of IoT technology or specific agricultural production management, they may need to gain such domain knowledge from more specialized books.

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Fei Liu is the deputy director of Institute of Agricultural Information Technology at Zhejiang University (ZJU), deputy director of the Key Laboratory of Spectroscopy Sensing at the Ministry of Agriculture and Rural Affairs, and a professor of agricultural engineering at the College of Biosystems Engineering and Food Science, ZJU. His research interests are in the areas of spectral/hyperspectral imaging and laser-induced breakdown spectroscopy (LIBS) for soil-plant-agricultural products information detection, remote sensing and agricultural IoT. He also worked as a visiting scholar at Hokkaido University, Japan. Dr. Liiu has authored/edited 5 books, published over 70 peer-reviewed journal articles, and been awarded 35 Chinese patents. Dr. Liu received his B.S. degree in engineering from China Agricultural University (CAU) and his Ph.D. degree from Zhejiang University (ZJU), both in China. Dr. Liu has been awarded one National Second Prize for Progress in Science and Technology in 2015; three First Prizes of Zhejiang Provincial Science and Technology Awards in 2012, 2014, and 2016; and two First Prizes of China's Ministry of Education Science and Technology Progress Award in 2014 and 2019.

In addition, Dr. Liu has been awarded Chinese Outstanding Patented Invention and DaBeiNong Science and Technology Awards-Intelligent Agriculture Award, both in 2017. He has also been nominated for the highly prestigious National Excellent Doctoral Dissertation Award in 2013.

Chapter 1
Introduction of Agricultural IoT

Yong He, Qin Zhang, and Pengcheng Nie

Abstract Agricultural IoT (Ag IoT), a term that refers to applications of IoT technology in agricultural production chain, brings together sensing, computing, and implementing devices to support need-specific operations, so that farmers can properly and promptly respond to the situation for improving yield and income. The adoption of Ag IoT can help farmers update their production from often low-efficiency traditional mode to a digital farming that is supported by demand-specific and time-sensitive production information. It can facilitate the expansion of farming management from in-production only to include both ends of pro-production and post-production so as to cover the entire operation chain, thus transforming agriculture from the productivity-driven business model to a market-driven model for best returns. This chapter lays an introduction of IoT technology, covering its origin, concept, and development status, followed by an elucidation of its architecture, features, and specific applications.

Keywords Internet of Things · Agricultural production chain · Digital farming · Field information · Need-specific operations

1.1 The Development of IoT

IoT stands for "Internet of Things," and the initial application of IoT technology could be dated back to the first US-Iraq war in 1991. As the war came to an end, the US military discovered that a large amount of supplies and containers were accumulated in different ports and airports. When dealing with post-war supplies, they encountered difficulties in getting prompt information of where exactly those items should be shipped and which department should manage them. Numerous

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human and financial resources were exhausted to acquire the accurate ownership status of those supplies. To solve the problem, the United States Department of Defense launched a project named Visual Management of Military Supplies, which adopted RFID technology for the intelligent identification and management of military supplies.

Learning from military successes, some US companies have begun to adopt this mighty technology for civilian uses. For example, UPS, FedEx, and other large logistic companies have adopted RFID technology to create shipment tracking systems that allow quick track and query of the shipments, leading to sound service evaluations. In the early application of IoT technology, its application mode manifested as an active interaction between human and "things," which laid the foundation for the development of IoT technology.

With the rapid development and integration of sensing, communication, and computing technologies, physical properties and spatial-temporal characteristics of the "things" became easier to obtain and process in real time. Information exchange between "things" gradually became realizable through data networking and communication technologies.

The concept of IoT was originally from Bill Gates' book (Gates et al. 1995) titled *The Road Ahead* but did not capture much attention at the time, probably due to the limitations of contemporary wireless network and sensing technologies. In 1999, the then Executive Director of Auto-ID Labs at MIT, Kevin Ashton, first formally introduced the concept of "Internet of Things" in his one speech (Foote 2016). Then in 2005, the International Telecommunication Union (ITU) further elaborated on the definition of IoT in its report titled *ITU Internet Reports 2005: The Internet of Things* and expanded IoT to include communication systems that connect humans and "things" or "things" and "things" in an Internet-enabled environment (Zhong 2012; Wang et al. 2016).

1.2 The Concept and Connotation of IoT

1.2.1 The Concept of IoT

Aforementioned, IoT was developed based on the Internet. Like the Internet, IoT uses communication networks as the medium, but unlike the Internet, it enables the interconnection between human/things and things. What is implied is that in IoT, the scope of client has been expanded to include any object. Briefly, IoT aims to connect all kinds of items via the Internet for perceiving, delivering, and sharing information. Through exchange of information, the world can evolve into a state where "all things can be connected." In short, IoT provides a handy tool for achieving intelligent monitoring and management for many applications.

IoT can connect ubiquitous end-devices, including those with "intrinsic intelligence," including sensors, mobile terminals, control systems in buildings, and household intelligence and video surveillance systems, and those with "external intelligence," covering RFID-attached assets and human or equipment with wireless terminals. These items can be interconnected, integrated, and remotely operated relying on various wireless or wired communication networks connected under IoT domains. Supported by appropriate information security guarantee mechanisms, IoT can provide safe, controllable, and personalized real-time online monitoring, tracing, alarming, scheduling, planning, remote controlling, decision supporting, and many more management and service functions. It also provides the base for integrating "monitor, management, and control" of "all things" in a high-efficiency, energy-saving, and safe environment.

1.2.2 The Connotation of IoT

Though IoT is built on the Internet, it goes beyond the scope of the Internet. One way to gain a comprehensive understanding of IoT technology is to compare its concept with that of the Internet.

First, it should be noted that IoT is not merely a new communication network; instead, it taps into the long-existing network communication technology and expands on that basis. As the Internet is a huge public communication network that accommodates almost all communication networks, IoT is just one of such communication networks built on the Internet for connecting "things" to exchange information with little or no human intervention in managing such exchanges. Physically, IoT interconnects those "things" using either wired or wireless or hybrid telecommunication networks to accommodate data tele-collection and dissemination (Zhang and Ehsani 2006).

As a huge global network woven by computing networks among human, the Internet provides a platform for information exchange among users. In comparison, IoT can connect "things" other than human, such as sensors, controllers, and even animals, plants, soil, and equipment to the Internet. Therefore, IoT is an extension of the Internet, an extension that includes non-human users. Sensors, controllers, and wired/wireless data communication networks are the essential elements for such extended capabilities.

From a broad perspective, with the rapid development of sensing, communication, and information technologies, future Internet, or the next generation of Internet, can connect human and "things" in a ubiquitous network via wearable devices. We can be interacting with others or "things" around us anytime and anywhere without even noticing it. In fact, although their names are different, there is no essential difference between IoT and the next-generation Internet. Both can interconnect humans via appropriate communication devices anytime and anywhere through any network to seamlessly exchange needed information with any person or device.

Defined narrowly, a communication network belongs to the category of IoT as long as it can interactively connect "things" via a data communication network, whether connected to the Internet or not. Other than exchange information between "things," an IoT can also seamlessly integrate existing public communication network to accommodate information exchange between human and "things" and form a ubiquitous network supporting smart world.

Although IoT is closely related to the Internet, they are also relatively independent networks. In an IoT, different systems and/or application terminals can co-exist in an interactive manner to support automated or remote perception and/or control functions. For different applications, the systems can be completely different: some may not share information with other systems, but some may engage in massive interactive data exchanges with other systems. Therefore, IoT, customarily, can be deemed as a collection of "ubiquitous network," which may or may not connect directly to each other, used in automated or remote monitoring, managing, or control applications. From this point of view, IoT and the Internet differ.

1.3 Development History and Present Situation of IoT

1.3.1 Development History of IoT

One of the first examples of using IoT-like technologies dated back to the early 1980s on a Coca-Cola machine located at the Carnegie Mellon University. Local programmers connected sensing devices to the refrigerated appliance via the Internet to see if there was a drink available, and if it was cold, before making the trip to get one (Veneri and Capasso 2018). The phrase "Internet of Things" as a concept was first formally introduced by Kevin Ashton, the then Executive Director of Auto-ID Labs at MIT, in his one speech at Procter & Gamble in 1999 (Foote 2016). In this speech, Ashton described a novel idea of using sensors (e.g., radio-frequency identification, RFID) to "tag" things, and it would involve the use of computers for the management, tracking, and inventory of those "tagged" things.

Since the concept of IoT was proposed, the general public have begun to notice applications related to IoT technology. On November 17, 2005, the International Telecommunication Union (ITU) released the *ITU Internet Report 2005* and formally proposed the concept of IoT at the World Summit on the Information Society (WSIS) in Tunisia (Zhong 2012; Wang et al. 2016). The report stated that the ubiquitous IoT Communication Age is coming and all objects in the world can actively exchange information through the Internet. RFID, wireless sensor networks (WSN), nanotechnology, and smart embedded technologies will be adopted more extensively. Countries around the world have also kick-started a wave of IoT development. For example, the United States, the European Union, Japan, South Korea, Australia, Singapore, and many other countries and organizations have successively launched research programs on IoT technologies for various applications. Those IoT applications would allow users to enjoy intelligent operation through intelligent processing (Liu and Zhou 2012). In an outlook report titled *Internet of Things in 2020: A Roadmap for the Future* published in 2008, the

European Union has pointed out that after 2020, EU countries are expected to form ubiquitous networks that integrate humans, machines, and "things" (Hai 2012).

1.3.2 Development Strategies of IoT in Various Countries

"Smart Planet" in the United States
The development of IoT technology and applications in the United States follows a clear "bottom-up" trajectory. In the early 1990s, the United States Department of Defense (DoD) regarded wireless sensor network (WSN) as a major field of research and created a number of related programs. The National Science Foundation (NSF) of the United States also developed WSN research programs that aimed to conduct systematic research on the basic theory of sensor networks. Constructing sensor subnet on next-generation Internet counts as a critical research topic. In addition, many manufacturers, such as Analog Devices, Freescale Semiconductor, and Ember Technologies, developed and commercialized various demand-specific IoT platforms or products.

In 2008, IBM proposed the concept of "Smarter Planet" with the strategic core of "cloud computing + Internet." After Barack Hussein Obama was elected as the President of the United States, he publicly endorsed this strategy (Bei 2017; Wu 2016). Under this strategy, the next step of IoT development is to fully adopt this novel intelligent information and network communication technology across the board. For example, the embedded or assembled sensors and other devices would be integrated into railways, highways, power grids, buildings, and bridges, giving rise to a state of interconnection among those objects. Then supercomputers and cloud computing would be used to process and analyze the acquired data from those objects to monitor their conditions, so as to realize the information exchange between the physical world and the computer for the eventual foal of seamless connection between "things" and "things" in IoT platforms. Since then, IoT has become increasingly widespread in all aspects of life in the United States.

In order to fully realize the potential of all the economic, social, and innovative benefits the IoT can deliver, and to achieve the widespread utilization of the IoT, in June 2016, Intel, Samsung, and the Information Technology Industry Council (ITI) launched the National IoT Strategy Dialogue (NISD), an initiative that brought together industry and organizational partners to jointly create strategic recommendations on IoT technologies to US policymakers (Zhang 2016). The US federal government actively responded to such endeavors. On January 8, 2020, the House of Representatives passed a resolution H.Res.575 proposed by Representative Bill Flores (R-TX) which stated that all stakeholders in the deployment of 5G communications infrastructure should carefully consider adherence to the recommendations of *The Prague Proposals*.

"IoT Action Plan of EU" for the European Union

The European Union (EU) has also made great efforts to scale up the applications and economic benefits of IoT. In June 2009, the EU Commission released a plan titled *Internet of Things – An action plan for Europe*, which acknowledged the opportunity of IoT, outlined its governance, and formulated 14 specific action lines (Song 2017). In September 2009, the European Research Cluster on the Internet of Things (IERC) issued *Internet of Things Strategic Research Roadmap*, which incorporated a common definition of the Internet of Things (IoT); provided the vision of "people and things to be connected anytime, anyplace, with anything and anyone, ideally using any path/network and any service"; and declared 17 IoT application domains, including food traceability, agriculture, and breeding (Dong 2012). Many European countries have created their specific plans for achieving the goal. For example, the Finnish Strategic Center for Science, Technology, and Innovation: For Information and Communications (ICT) Services, businesses, and technologies released a research agenda "Internet of Things Strategic Research Agenda (IoT-SRA)", specifying IoT research mission, targets, research themes, and applications for Finland (Ailisto et al. 2011; Dong 2012).

At present, the EU has made breakthroughs on IoT applications in small-scale farming, precision livestock farming, and intelligent fisheries. Among those, greenhouse IoT in the Netherlands is highly developed, taking the leading position in terms of intelligent management and environmental control of greenhouse. According to *Internet of Things in 2020: A Roadmap for the Future*, it was expected that EU countries will make any object intelligent and form a ubiquitous network connecting human beings, machines, and "things" after 2020 (Hai 2012).

"u" Strategy in Japan and South Korea

Adhering to its strategy of establishing "the world's most advanced IT nation," Japan was one of the leading countries with regard to launching IoT applications. The Japanese approach of IoT development went through four stages of e-Japan, e-Japan II, u-Japan, and i-Japan. The e-Japan strategy was issued by the Japanese IT Strategy Headquarters in January 2001 which was mainly focused on constructing broadband infrastructure for the nation (Zhou 2012). It included the declaration of four priority policy areas of (1) establishing the ultra-high-speed network infrastructure; (2) facilitation of e-commerce; (3) realization of e-government; and (4) nurturing high-quality human resources. Since the e-Japan I strategy was completed ahead of schedule, the Japanese government launched an e-Japan strategy II in July 2003, which was the blueprint of the second phase development of "advanced IT nation" (Zhou 2012). The second phase strategy shifted its focus from "IT infrastructure development" in the previous phase to "effective IT utilization" by identifying seven leading areas in promoting such utilization, including medical services, food, lifestyle, small and medium enterprises financing, knowledge, employment and labor, and public service. In 2004, the Ministry of Internal Affairs and Communications (MIC) of Japan formally announced the u-Japan Policy, which provided guidelines for the creation of a seamless and ubiquitous network in which people can receive services without noticing the existence of the networks (wired or wireless). This Policy aimed at stimulating efforts to build Japan into a country that anyone and anything can be connected at anytime and anywhere before 2010 (Zhou 2012). After the global financial crisis, Japan's IT Strategy Department released a medium- and long-term development strategy of IT technology, *i-Japan strategy 2015*, in July 2009 as the strategy to achieve quick economic recovery. This strategy aimed to improve Japan's global competitiveness by building a digital Japan. In recent years, the Japanese government has shifted its development focus to intelligent cloud, promoting the integration and sharing of massive information and knowledge in the Japanese social system with the help of cloud services.

Similar to Japan, South Korea has also incorporated IoT into its national IT development plans at a very early stage. For example, the *Cyber Korea 21 Initiative* released in 1997 was focused on the popularization of the Internet (He 2004). Since then, from the deployment of RFID, cloud computing promotion, to other relevant technological breakthroughs, the South Korean government has successively issued many national informatization construction plans. Among them, the u-Korea strategy was one of the major strategies aimed at the popularization and application of IoT in South Korea. Started in March 2004 by its Ministry of Information and Communication Industry, South Korea established a u-Korea strategic planning group which set up a 10-year u-Korea strategy. According to that plan, the development period of u-Korea is 2006–2010, and the maturity period is 2011–2015. Based on the best ubiquitous WSN in the world, this strategy intended to make all resources in South Korea digitized, networked, visualized, and intelligent and to build South Korea the first ubiquitous society in the world, thus promoting the economic development and social transformation.

"Sensing China"

As early as 1999, the Chinese Academy of Sciences initiated the research on sensor networks and designed a number of sensor networks suitable for different sensing technologies. On August 2009, the then China Premier, Mr. Wen Jiabao, propositioned a concept of "Sensing China" during his visit to Wuxi Micro-Nano Sensor Network Engineering Technology Research Center. Since then, IoT has been officially listed as one of the five emerging strategic industries in China and was included in the "2010 Government Work Report" (Qian 2015). In China's 12th Five-Year Plan, IoT was clearly regarded as one of the strategic emerging industries and was strongly supported by the government (Li 2012). It was specified in the plan that the Chinese government would focus on promoting demonstration projects and leading roles in nine fields, including smart industry, smart agriculture, smart logistics, smart transportation, smart power grid, smart environmental protection, smart security, smart healthcare, and smart home. China hoped to achieve a number of remarkable breakthroughs in the research, development, and industrialization of IoT by 2015. This goal included the breakthrough of core technologies, the creation of key national standards, the demonstration of the technology via impactful applications, and the initialization of industrial chains. The approach China planned to take was innovation-leading, application-driven, cooperation-based, safe, and controllable (Chen 2013). On March 5, 2015, China's Premier, Li Keqiang, announced an *“Internet +” Action Plan* to promote the integration of mobile Internet, cloud computing, big data, and IoT technologies with modern industries. For instance, “Internet + Agriculture” is one of the efforts. As of June 2019, rural Internet users in China reached nearly 0.225 billion, accounting for 26.4% of China’s Internet users. Thanks to the guidance of government policies and the support of broad recognition of the technology, sufficient conditions were created for the development and adoption of “Internet + Agriculture” technologies, which can bring China’s agriculture to a new height.

1.3.3 Typical Industrial Applications of IoT

Smart City

Smart City is an advanced form of urban informatization development supported by IoT technologies. The backbone of a smart city is different types of IoT networks which connect different types of sensors spread all over the city for data collection. Supported by big data and cloud computing technology, the insights gained from the collected data were then used to manage all functions, services, and resources in a manner that is effective and efficient. The data collected from citizens, devices, and resources enables the monitoring of the status of critical city operations and almost all aspects of life, covering telecommunication, traffic and transportation, food supply and safety, water and utilities supplies, public health and security, and other essential community services. Aiming at providing improved services to the community, Smart City may also require the use of social networks and other tools to ensure that it will be a people-oriented and comprehensive yet still highly efficient system of urban operation management. A smart city shall have to integrate administrative management, urban planning, emergency respond systems, and other social services. To optimize the efficiency of city operations and services, and to connect them with citizens, smart cities will fully utilize information and communications technologies (ICT) and various physical devices connected to the IoT network. Smart cities also allow city authorities to interact directly with both community and city infrastructure and to monitor what is happening in the city and how the city is evolving.

Smart Healthcare

To gather, store, and process various types of medical data for providing improved care to patients and enhanced technologies to providers, Smart Healthcare depends on IoT as an enabler to seamlessly interconnect patients, healthcare providers, and implantable or wearable medical devices. Equipped with such connectivity among patient, providers, and devices, Smart Healthcare would allow providers to better treat patients using better diagnostic tools, more devices (by taking advantage of external resources), and enhanced expertise (which might be more important for some special cases when local expertise is insufficient). It can enable providers to assist patients in their homes where they can be continuously monitored with the help of numerous Internet-connected healthcare systems and devices. This approach reduces the need for hospitalization, which can be especially beneficial to elderly. In addition, a smart healthcare system can allow patients and health service providers to take advantage of connected medical services by delivering patient's medical data to their health service providers, thus offering a proactive approach to early detection and even prevention of medical conditions. All above can potentially mean significant improvement of life quality for patients and markedly reduced healthcare costs. In summary, Smart Healthcare helps hospitals deliver truly patient-centered medical services through prompt and improved patient care, more effective ways of healthcare delivery, more efficient use of resources, and reduced costs.

Smart Transportation

Smart Transportation, one of vertical applications of IoT technology to transportation systems, is an advanced stage of intelligent transportation that aims to better inform users and to enable them making safer, smarter, and more efficient use of transport networks. The core functions include perception, data mining and analysis, and interconnectivity of vehicles, roads, and control center, all of which realized through integrating sensing, IoT, cloud computing, artificial intelligence, and automatic control technologies with smart management strategies. Smart Transportation provides a real-time interactive information service platform for achieving optimal traffic control and planning at local, regional, and even country level in both temporal and spatial scales for meeting transportation needs of all aspects. Smart Transportation can also include the use of some other innovative technologies, such as vehicle navigation, fleet management, toll and parking services, traffic signal control, and traffic law reinforcement. Such adoption significantly improves overall transportation efficiency and traffic safety to meet the safer, faster, smoother, and more reliable transportation needs of individuals and businesses alike.

Smart Logistics

Smart Logistics, another vertical application of IoT technology in the supply chain, adopts connected devices, such as RFID, GPS, wireless network, mobile Internet, and other intelligent tools, to bring end-to-end visibility in the process of supplying the right product at the right time and the right place and in the right condition to the customer. This IoT-integrated system can utilize data from diverse sources of various formats, in either static (e.g., inventory records) or dynamic (e.g., delivery tracking information), to acquire and analyze needed information for making adequate decisions, decisions that will make supply chains more effective and efficient at each step. For example, a sensor-driven and IoT-connected asset tracking tool can provide users with real-time visibility at each stage of shipment. Such visibility may include conditions of shipment, such as moisture, heat, vibration, and any other interested parameters as the product moves through the supply chain, thereby ensuring sensitive supplies are being handled under right conditions during the entire process. Integrating artificial intelligent technologies, Smart Logistics makes logistics systems imitate human intelligence and bestow upon them the ability of perceiving, learning, and reasoning, allowing them to solve unexpected problems in logistics.

Smart Campus

Smart Campus is an in-depth integration of information technology and teaching. Supported by IoT, cloud computing, and big data analysis, a smart campus system employs various application systems to create a smart learning environment that entails all aspects of campus life, from teaching and scientific research, to student activities and leisure, and to management and decision-making. In general, Smart Campus have three core functions, i.e., providing (1) personalized services to teachers and students using a comprehensive intelligent environment and information service platform; (2) seamless information services to teachers and students by integrating various applications and services using a networked computer system; and (3) an interface for mutual communication and mutual perception between the school and the outside world. Some smart campus products have already been developed, such as smart school gates, future classrooms, electronic fences, smart buildings, etc.

Smart Home

Smart Home is the embodiment of Internet-enabled household interconnection. Developed for residence house, Smart Home adopts integrated cabling technology, network communication technology, security technology, automatic control technology, and audio and video technology to connect various devices in the house for building efficient residential facilities and family schedule management system. Smart Home can provide a variety of functions, such as remote control of home appliance, lighting, telephone, indoor and outdoor security monitoring, environmental monitoring, and other programmable devices. In addition, Smart Home can offer a full range of information interaction, thus improving home safety, convenience, comfort, and aesthetics and bringing environmentally friendly and energy-saving lifestyles.

Smart Grid

As an IoT-supported power grid intelligent management system, Smart Grid integrates sensing, communication, computing, and control technologies with a power grid for improved grid management. Aiming to best satisfy user's demand for electricity, a smart grid system manages a grid by taking safety, reliability, economic, and environmental regulations into consideration when optimizing the grid operation. A typical smart grid system consists of four subsystems, including sensing, transmission operation, distribution control, and asset management.

Smart Manufacture

Smart Manufacture is a penetrating and in-depth application of IoT technology in manufacturing industry. It can incorporate, on an on-going basis, into all aspects of industrial production various types of terminals with the ability of situational perception, computing models based on ubiquitous technology, and wired or wireless communications. Therefore, Smart Manufacture could potentially improve manufacturing efficiency and product quality and cut down production costs and resource consumption. The application of IoT in manufacturing is also reflected in supply chain management, production process automation, product and equipment monitoring, safety and environment monitoring, and energy management.

Smart Agriculture
Smart Agriculture is a farming management concept that relies on modern information and communications technology (ICT) to improve both the yield and quality of agricultural products through data-enabled production management. Agricultural IoT systems provide the infrastructure required to interconnect sensors, big data processing and knowledge-based decision-supporting tools, artificial intelligence, and automated implementing equipment for smart agricultural production. For example, an IoT system can integrate various sensing systems for the precise measurement of temporal and special variations of soil and crops within a field. The system can also incorporate a remotely connected intelligent data processing unit for the analysis of the obtained data, thus extracting information that supports decision-making. Furthermore, the system can also incorporate a control center for monitoring and decision-making and an electronic controller for automatic field operations. Similarly, applying IoT-integrated smart agriculture technology to animal farming can help farmers achieve precise feeding based on the monitored needs of individual animals and purposely prevent disease and enhance herd health according to the potential health hazards detected. Various sensors and data communication networks will play critical roles in these smart agriculture practices. Defined more broadly, Smart Agriculture should or could expand its scope to include agricultural e-commerce, product traceability, agricultural leisure tourism, and other relevant aspects, as those components can also impact the productivity, product quality, and profitability of agriculture production. Targeting at upgrading agriculture with respect to the entire production-supply chain, and enhancing agriculture sustainability and competitiveness, Smart Agriculture is an inevitable trend of global agricultural modernization (Lehmann et al. 2012; Talavera et al. 2017; Khanna and Kaur 2019; Villa-Henriksen et al. 2020).

1.4 Agricultural IoT System

1.4.1 Architecture of Agricultural IoT

Agricultural IoT (Ag IoT) is a vertical application of IoT technology in agricultural production, management, and services. It mainly works to connect various sensors and data transmitting networks to promptly perceive major operational information from production sites. Through adequate process and analysis of the obtained data, Ag IoT enables more effective production management by optimizing operation the operation, thus increasing yield and income. The effective integration of IoT and

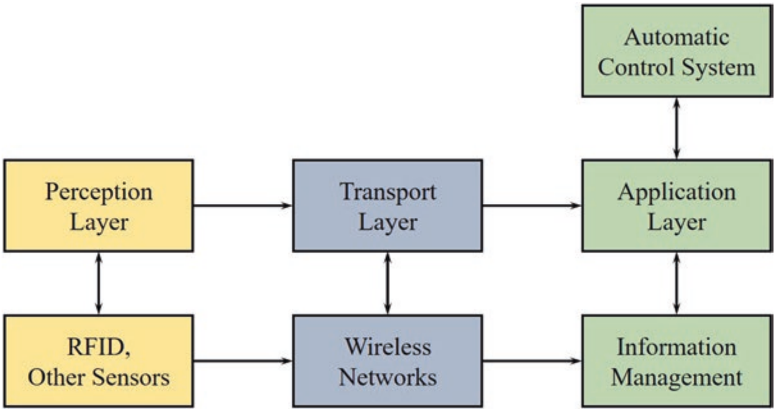

Fig. 1.1 The relationship between three layers of an Ag IoT architecture

agriculture would transform agricultural production from the traditional low-efficiency mode to a data-based intelligent production mode that is focused on higher productivity and profitability.

The typical architecture of an Ag IoT is primarily composed of three layers: the information perception layer, the transmission layer, and the system application layer (Fig. 1.1). Among them, the core components of the information perception layer are sensors. Similar to human's reliance on their vision in observing crop growth conditions, sensors are relied on to acquire dynamic and real-time information. The perception layer in an Ag IoT collects multi-dimensional information of crops, soil, and environment via various sensing technologies. Such information includes, for example, the nutrients, moisture, and vegetation index of crop; the moisture, organic matter, and nutrients of soil; temperature; humidity; light intensity; and so on (Fig. 1.2). The information transmission layer transmits data collected at the perception layer. In Ag IoT, Zigbee, LoRa, GPRS, Wi-Fi, and Bluetooth are commonly used wireless networking means for the transmission of data. The technologies involved mainly include intelligent self-organizing network protocol, low-power and high-reliability transmission mechanism, and so on (Fig. 1.2). System application layer, including intelligent information management system and automatic control system, is used to host data processing, information analysis, intelligent reasoning, and implementation control elements, a function that supports the automated processing of agricultural data, decision-making, and control of agricultural production. Figure 1.3 is a graphic illustration of the basic framework in which this three-layer architecture supports information perception, data transmission, and data analysis for decision-making and for implementing automated control at last (Nie 2012).

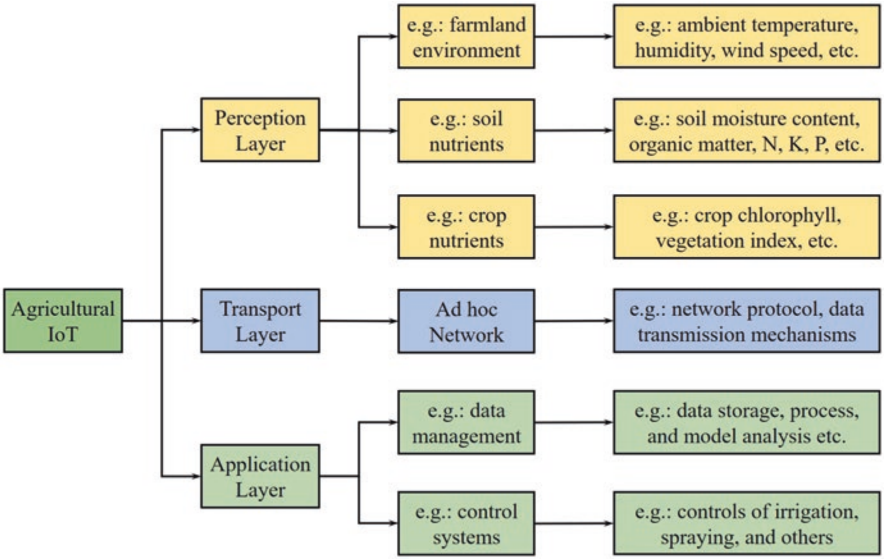

Fig. 1.2 The composition of Ag IoT planting intelligent system

1.4.2 Features of Agricultural IoT

As a wirelessly self-organizing network, IoT has been extensively adopted by many industrial automation systems. Since the end of the twentieth century, developed countries such as the United States, the European Union, Japan, and China have launched research programs on WSN one after another. Well-known programs include SensorIT, WINS, SmartDust, SeaWeb, Hourglass, SensorWebs, IrisNet, and NEST. In the United States, the US Department of Defense, NASA, and other federal agencies have invested heavily to support the research and development of IoT technology.

While Ag IoT is a vertical application of IoT technology in agriculture, there are a few essential differences, mainly on application conditions, between the IoTs for industrial applications and for agriculture. One such difference is the special requirements on network communication protocols for agricultural applications. The network protocols for Ag IoT demand the connection of mobile farm machinery, high-moisture working environments that include in-field irrigation sites, greenhouses, chemical spraying operations, and even animals. In addition, the microclimate of various agricultural productions has certain impact on wireless communication, and the continuous changes of growth states are also likely to exert major impacts on wireless transmission. On the other hand, some of the acquisition of agricultural information do not have to be completed in real time, and a certain degree of delay in the transmission process of such data would not cause much trouble. What all these complicated issues mean is that Ag IoT (He et al. 2013). The

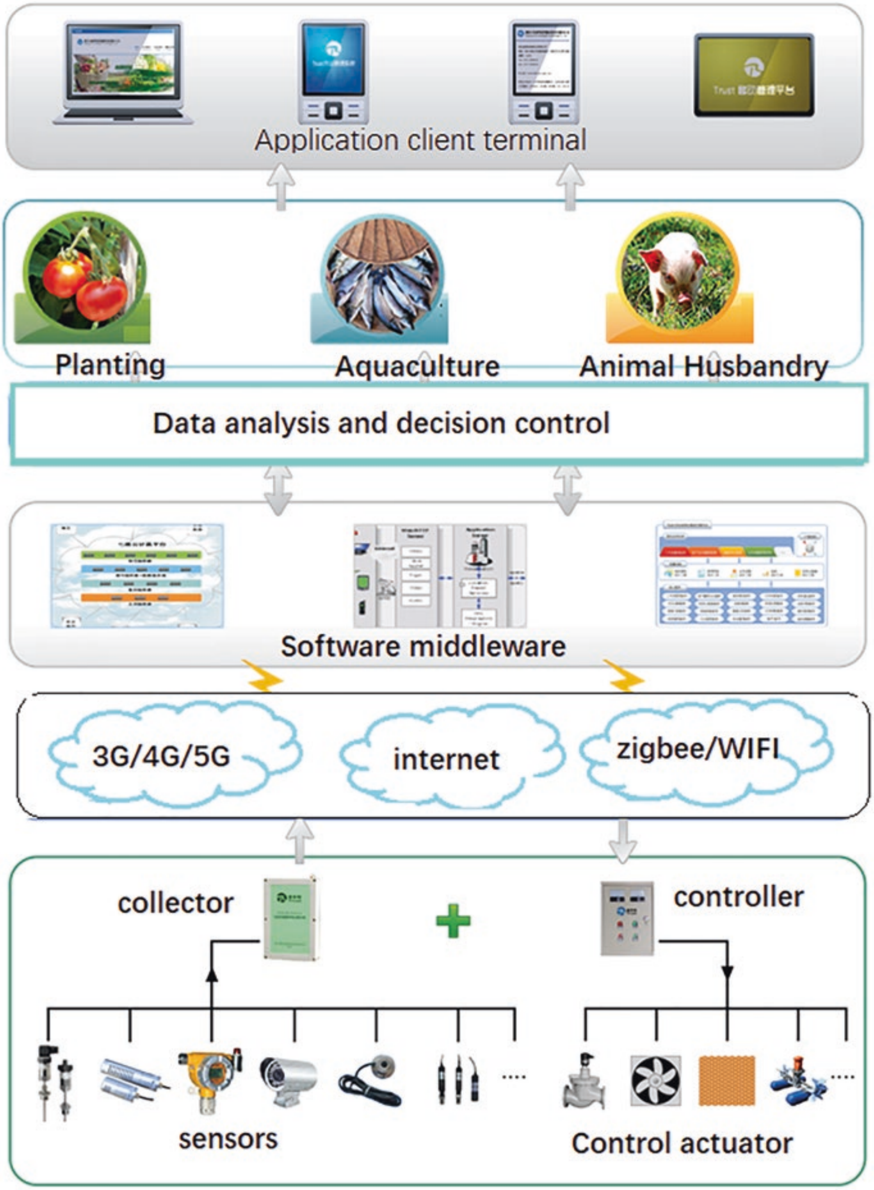

Fig. 1.3 The basic framework of Ag IoT

following sections will briefly introduce some features of sensor nodes and other field devices in an Ag IoT.

1.4.2.1 Sparsely Arranged with Relatively Fixed Locations

In comparison to industrial production, agricultural production generally operates in a low-input and low-output mode, which makes it difficult to densely deploy sensor nodes to acquire production-related data. In addition, deploying too many sensor nodes in a field can also interfere with normal field operations, especially in mechanized operations. Therefore, the sensor nodes in Ag IoT are sparsely arranged, and a relatively long distance between the nodes is often required. To collect the typical data from a large area of agriculture sites, one common practice is to divide a field into multiple sampling zones and place one sensor note in each sampling area. Such practices are founded on an assumption that the soil, crop, and environment parameters in this sampling area maintain approximately constant values, so that the typical data can be determined. As many of the agricultural lands are confined by natural boundaries, such as roads, rivers, and terrain edges, with some irregular shapes, the zoning of sensor nodes is also often irregularly determined. Once the sensor nodes are installed, their locations are rarely adjusted for collecting comparable temporal data from the field.

1.4.2.2 Long-Distance Data Transmission and Low Power Consumption

In typical Ag IoTs, a long distance of wireless data transmission is generally required between in-field sensor nodes, and their distance to the data receiving center and the control platform could also be far away. What this means is that long-distance wireless transmission of the data collected by sensors is essential in many agricultural applications, especially for those deployed to farmland. In addition, the sensor nodes placed in farmland often rely on batteries or solar chargers for power supply. Therefore, it is highly desirable to have sensor nodes featured low power consumption suitable for long-term use.

1.4.2.3 Working Under Extreme Environment

Agricultural production is generally conducted in natural environment where extreme conditions frequently appear, such as abnormally hot or cold temperatures, heavy rain/snow falls, or super strong winds. IoT devices installed in field are expected to work properly and reliably under all those conditions. Therefore, one fundamental requirement for Ag IoT devices deployed in field is the ability to cope with such extreme environment conditions, especially the resistance to extreme temperatures and waterproofing. In addition, field workers often lack the ability to perform routine maintenance of IoT devices. This makes it more challenging to keep Ag IoT devices stable, reliable, and durable with minimum maintenance needed. If possible, certain self-diagnosis and automatic tuning or adjustment functions are highly preferred.

1.4.3 Application of Agricultural IoT

In the past couple decades, many countries, such as the United States, the European Union, Japan, and China, have undertaken a number of research programs on applying IoT technologies to agriculture. The applications of IoT in agriculture include field automation of crop and animal production and automation of agriculture and food supply chain. Such applications offered farmers with data-enabled and practical means for interactively managing their production in a more effective and efficient way. At the same time, it also promotes the interconnection of Ag IoT and other IoT applications, contributing to the establishment of ubiquitous IoT. While some products of sensing devices, connectable to IoT, became commercially available, most of them are still in the development and experimental stage. A large space of improvement still exists with regard to important performance parameters of products, such as stability, reliability, and power consumption.

1.4.3.1 Application in Field Crop Production

In production, the applications of IoT mainly include the continuous monitoring of field conditions, which enables a few automated functions. For example, the sensing unit monitors plants and/or soil water or nutrient stresses to provide the needed information for automatic irrigation or precision fertilization. Hamrita and Hoffacker (2005) developed a prototype system which integrated a few sensors using RFID tags to monitor comprehensive soil information in real time. Zhang et al. (2009) designed a multi-sensor information monitoring system for growth information that includes crop spectra, multispectral image, canopy temperature, ambient temperature and humidity, and light on canopy. The system monitors crop nitrogen and water stresses. To improve the management of wheat production, Xia et al. (2013) developed an IoT-based remote diagnosis and management system for wheat seedling, which measures the physiological and ecological characteristics of wheat. Additionally, the system is fused with historic weather disaster indicators to create adequate wheat management plan for different growth stages under disastrous weather conditions. A few other examples include the development of a farmland environment monitoring system based on WSN reported by Bhanu et al. (2014), an innovative multi-agent system based on virtual organization reported by González-Briones et al. (2018), and a remote monitoring system for drip irrigation based on solar power designed by Liu (2019).

1.4.3.2 Application in Aquaculture and Livestock Farming

In aquaculture, Ag IoT is primarily used to monitor water quality and aquatic product conditions for regulating the carbon dioxide concentration, temperature, and feed, so that optimal growth conditions can be created. Meng et al. (2015) developed an online monitoring system that consisted of an automatic cruise drone, an environmental monitoring device, and a remote service platform. This system was installed on an unmanned ship which can be automatically and safely guided to desired sampling points to perform location-specific measurements on water temperature, dissolved oxygen, pH value, redox capacity, as well as ecological information of fish and shrimp. Parra et al. (2018) developed a system to monitor water quality, feed conditions, depth, and speed of swimming in aquaculture ponds. In addition, this system contained an intelligent energy management algorithm for the automatic control of data transmission using an energy-saving mode. Sun and Chen (2019) designed an IoT water quality monitoring system to remotely monitor and manage water quality in terms of water temperature, dissolved oxygen, pH, and a few other parameters.

An enabling environment for livestock and poultry production can effectively prevent and reduce the incidence of diseases and promote the rapid growth of livestock. IoT here is mainly used to monitor the production environment and animal conditions, thereby realizing automated control, which creates optimal growth environment. For example, Godas et al. (2015) designed a sensor-based system called Sheep Manager for monitoring and managing sheep milk production. The system adopted near-field communication (NFC) technology to identify sheep and used sensors to measure and record milk yield of individual ewe in real time. Saravanan and Saraniya (2018) developed a livestock management system based on cloud IoT which employed UID identified wearable collars as sensors to monitor and record physiological parameters of animals, such as body temperature, standing, eating, heartbeat, as well as ambient air temperature and relative humidity, to perceive and predict animal's health status. To develop adequate methods for livestock facility monitoring, Li (2018) conducted a parametric study that combined multiple technologies including signal processing, intelligent computing, and machine learning to determine the impact of some commonly measured parameters on the overall environment.

1.4.3.3 Agricultural Logistics

Qian et al. (2012) developed a wheat flour traceability system (WFMTS) which combined barcode and RFID technology. This system has been put to use in a wheat flour mill in China. Li et al. (2017) proposed an IoT management platform capable of tracking the supply chain of prepackaged food in real time. Integrating QR codes and RFID tags, this platform enabled fine-grained tracking of the supply chain at low costs. In order to track food logistics in real time, Tian (2017) attempted to build a traceability system for food supply chain based on hazard analysis and critical control points (HACCP) and blockchain and IoT technologies. Wang et al. (2018) designed a wireless multi-sensor system to monitor and analyze key parameters of fresh-cut branches of North American holly, including temperature, relative humidity, and concentration of carbon dioxide and ethylene in the cold chain environment. According to the results of the analysis, the cold chain environment can be improved, and early warning can be provided to improve the post-harvest quality of fresh-cut branches of North American holly.

1.5 Development Prospects of Agricultural IoT

It is reasonable to expect that Ag IoT would evolve into a ubiquitous system that gives identities to everything, ranging from a cow to an apple tree, thus keeping consumers informed about where their foods were grown or raised as well as how were they grown, processed, and handled throughout the entire supply chain. Such functions ensure the purchase of safe and nutritious food. Interconnection of all agricultural and food products can be truly realized. In a nutshell, Ag IoT will penetrate into the whole process of agriculture and food production chain and play a huge role in human life.

1.5.1 New Opportunities for Agricultural Sensor Research

As the “eye” for perceiving information related to agricultural production, field sensing technology plays a vital role in the information perception layer of Ag IoT. Some of the common requirements for developing new field sensors include low costs, low maintenance, self-adaption, high reliability, and low power consumption.

1.5.2 Integration of Agricultural IoT and Automated Field Machinery

As a general trend, agricultural machinery now features more automatic and/or intelligent functions, some of which are now wholly autonomous. As the executive link in IoT-supported agricultural operations, agricultural machinery should evolve into an automatically or remotely controlled in-field execution system of the IoT. For example, IoT-supported variable fertilizing operation would require automatic or remotely controlled real-time application. Such operations demand effective and reliable data communication between the IoT system and the mobile field machinery. A machine area data network (Zhang 2007) can serve as a node for integrating a mobile field machinery with an Ag IoT system to achieve effective and reliable data communication.

1.5.3 Integration of Agricultural IoT and Food Supply Chain

As a technology capable of monitoring the entire process from production, processing, transportation, to circulation/consumption of agricultural products, Ag IoT will play increasingly important roles in the food supply chain, roles like providing the needed traceability for food safety (Christopher et al. 2017). Traceability allows consumers to be aware of how their foods were produced, for instance, what fertilizers and pesticides were used under what condition; how was it processed, stored, and/or transported under what safety/quality control measures; and how was it handled in the circulation/consumption stage. Thus, the integration of Ag IoT system and food safety traceability system will provide an effective and practical means to ensure food safety and protect consumer rights.

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Chapter 2
Agricultural IoT Standardization and System Applications

Yong He, Yu Tang, Qin Zhang, and Yiying Zhao

Abstract The general application of agricultural IoT is to set up a large number of sensor nodes, so that a monitoring network can be formed, collecting information through a variety of sensors to help agricultural workers with the identification of problems. The adoption of agricultural IoT will transform agriculture from a human-dependent production mode into an information-based and software-centric production mode, involving the extensive use of various automated and intelligent production equipment. This chapter introduces the concepts of standards, standardization, and standard systems at length and summarizes the concept of the agricultural IoT standard system. Finally, it offers a brief introduction of the standards and specifications involved in each layer of the agricultural IoT system.

Keywords Standard · Standardization · IoT standardization system · Agricultural IoT

2.1 Introduction

IoT refers to the ubiquitous network consisting of ubiquitous end devices and facilities, including sensors with "intrinsic intelligence," and mobile terminals. IoT is simply defined as the exchange of information between "things" and "things" of the same attribute. In today's world, IoT enables interactions between objects with

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different attributes or different systems. For example, in agricultural IoT, the production and processing of agricultural products are seemingly completely unrelated, but food safety traceability can fully realize the interaction of these two kinds of different information. To achieve the seamless connection of information, interaction between these two dimensions must share an inevitable and unique correlation, and the standardization of information is the only way to complete the seamless connection of information in different spaces and dimensions.

Against the backdrop of the rapidly maturing IoT technology, an ever-larger giant network of information is being formed. Every object and every person circulate in this network as an information element that comes with unique features. The linking of different behaviors, attributes, and events depends on the standardization of information within the network. Information standardization is the foundation for promoting the vigorous growth of information technology and also the prerequisite for information sharing. Broadly defined, information standardization involves not only the expression of information elements but also the entire processing of information, including information transmission and communication, data flow, information processing techniques and methods, information processing equipment, and so on. The high-speed development of IoT technology and the advanced integration of information must follow unified standards and rules. Standardization is inevitable to the development of IoT. Furthermore, such standardization is conducive to the standardization and interoperability of various industries in different industries and different business processes, thus facilitating IoT connection and the related ubiquitous information network.

At present, an initial framework has been laid for China's IoT standard system. A number of proposals on standardization submitted by certain organizations to the International Organization for Standardization have been adopted. Initial progress has been achieved in the standardization of IoT. Figure 2.1 is an illustration of the basic framework of IoT standardization.

The process involved with IoT standardization is highly complex. There ought to be relevant standards for all links, applications, or industries in IoT, and agricultural IoT is no exception. In the process of agricultural IoT standardization, the relevant standards are generally formulated at three levels.

- Standardization of the perception layer: the perception layer contains perception control components, perception control gateways, and sensor networks to sense and control the physical world and to convert the information into a prescribed data format and send it to the network layer. The standardization of the perception layer is mainly concerned with common features and technical requirements in terms of interfaces, communications and networks, collaborative information processing, information service support, network security and privacy, consistency, and interoperability testing.
- Standardization of the transmission layer: the IoT transmission layer is divided into the wired communication transmission layer and the wireless communication transmission layer. Wired communication technology includes a medium- and

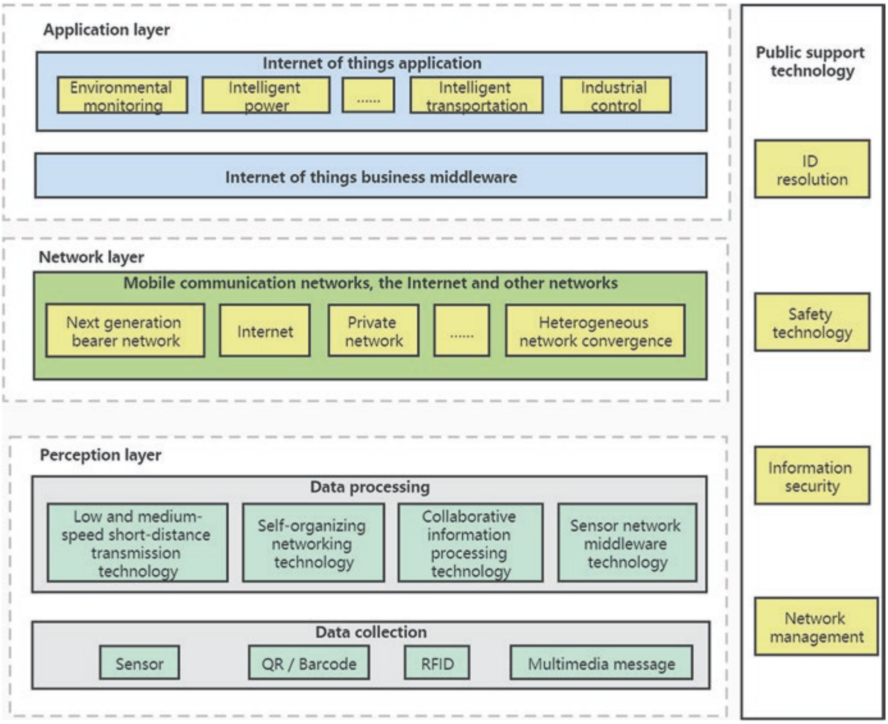

Fig. 2.1 Basic framework of IoT standardization

long-distance wide-area network and a short-distance fieldbus, while the wireless communication layer is divided into a long-distance wireless local area network, a short-distance wireless local area network, and an ultra-short-distance wireless local area network. Standardization of the transmission layer formulates the information transmission specifications and standard interface protocols under different transmission systems. In particular, it establishes the standardization of information connection under different communication modes to achieve the intercommunication of information in different transmission modes.

- Standardization of the application layer: the application layer is engaged in information processing through the cloud computing platform. It can calculate, process and mining the data collected in the perception layer for different applications. The related standardization shares a close correlation with the management process and information processing mode. For example, each subsystem should be provided with standard information interfaces and control interfaces. While achieving the interconnection between “things” and “things,” it can also realize “things” and “things” control.

2.2 Concepts of Agricultural IoT Standards

2.2.1 Standard

In 1983, in China's GB 3935.1-83 *Basic Terms of Standard Technology*, standard was defined as: "standards are unified provisions for repetitive things and concepts." They are based on the comprehensive results of science, technology, and practical experience and are agreed upon by the relevant parties, approved by the competent authority, and issued in a specific form as guidelines and basis for mutual compliance.

- The essential attribute of the standard is a "uniform regulation." This unified provision serves as the "common guidelines and basis" for all parties concerned.
- The scope for setting standards includes repetitive things and concepts. The "repetitiveness" mentioned here refers to the nature of the same thing or concept appearing repeatedly. Although the scope of formulating standards has expanded from production and technology to include various fields of economic and social undertakings, standards are not applicable to all things or concepts; rather, they are suited for stable and repetitive things or concepts.
- Standard is based on the "combination of science, technology, and practical experience." These achievements and experience must be analyzed, compared, integrated, and verified based on standardization. Only in this way can the standards formulated be scientific.
- In the process of formulation, standards must "obtain the consensus among relevant parties." What this means is that standards should not be decided by minority groups; instead, democracy should be promoted, and consensus should be reached among all parties concerned. For example, the formulation of product standards must involve not only the producers but also consumers and research and inspection departments, so that the standards formulated are authoritative, scientific, and applicable.
- The essential characteristic of standards is unanimity. That is, the standard must be "approved by the competent authority and issued in a specific form." A set of working procedures and approval systems, from the formulation of standards to their approval and release, is in place.

2.2.2 Standardization

GB 3935.1 defines standardization as "in social undertakings, such as economics, technology, science, and management, repetitive things and concepts are formulated, published, and implemented to achieve uniformity, so that the optimal order and social benefits could be delivered." The meaning of this definition is as follows:

- Standardization is an activity. Where there is human activity, the problem of standardization arises. Humans are engaged in activities, in order to obtain the required product or the optimal order. The major components of standardization activities include the exploration of the law of development, the formulation and execution of standards, and the supervision of the implementation of standards.

- The process of such activities is a continuously expanding one. For example, in the past, only product standards and technical standards were formulated. Now management standards and work standards must also be formulated. In the past, standardization was mainly a thing in the field of industrial and agricultural production. Now it has been expanded to the area of safety, health, environmental protection, transportation, administrative management, information codes, etc. As human societies move forward, the scope of standardization will continue to expand and deepen.
- Standardization is a process of understanding, i.e., the process from practice to knowledge to practice and to the reacquisition of knowledge. As knowledge deepens, improved understanding can be expected. The objective law of the development of things must not be violated. Standardization is to promptly respond according to the degree of understanding and the predictability of the law of development of things. As the understanding of the objective law of things gradually deepens, new questions, new demands, new approaches, and new methods are constantly raised. In the process of understanding, standardization keeps pace with scientific and technological progress and seeks laws, methods, and platforms.

2.2.3 Standard System

Standard systems are organic wholes composed of a number of standardized documents that are interdependent, interacting, and equipped with specific functions. The internal standards of standard systems should be logically combined according to a certain structure, instead of being piled up in a disorderly manner. Due to the complexity of standardization objects, the logical structure of different standard subsystems in the system may reflect different forms of expression, mainly including two types of hierarchy and linear structure. Standard systems generally consist of block diagrams, developed diagrams, and detailed lists. The block diagram and the developed diagram are standard architecture diagrams, and the detailed list lists the position number, name, standard number (including the standards developed and preferred by the user), maturity, and other information of each standard one by one according to the structure diagram.

The primary role of standardization systems is that it is the framework of standardization. Standard systems indicate what standards are required to achieve the specific goals, the content of such standards, interface, and the interrelationship of these standards. Standard systems optimize the overall structure to avoid the omission and duplication of standards. Moreover, they establish the priority of standards, hence proposing the overall design plan for standardization. Standard systems provide the basis for the planning and arrangement of standardization (Chen and Zhao 2011).

2.3 IoT Standardization System

The International Telecommunication Union (ITU-T) and the European Telecommunication Standardization Institute (ETSI) M2M Technical Committee are the typical international standards organizations. According to research undertaken by the International Organization for Standardization, standardization of IoT is mainly divided into three levels (Chen and Zhao 2011), which are related studies on standard systems at the perception layer, transmission layer, and application layer, including IEEE 802.15.1 and other standards.

2.3.1 IoT Perception Layer Standardization

The perception layer relies on sensors to obtain data and information generated in the physical world. Additionally, it may involve the use of radio-frequency identification (RFID), two-dimensional code, real-time positioning technology, automatic identification and data capture (AIDC), and other technologies. The standardization of the IoT perception layer includes the standardization of sensor information, the standardization of data formats, the standardization of data collection, and the standardization of embedded hardware operating systems.

The standardization system of the IoT perception layer is illustrated in Fig. 2.2. Perceptual standards are refined according to the common characteristics and technical requirements of the IoT perception layer, including technical terms, interfaces, information formats, information descriptions, information identity consistency, and interoperability uniformity and standardization. Doing so makes information universally adaptative and compatible in different systems and increases the accuracy and reliability of information.

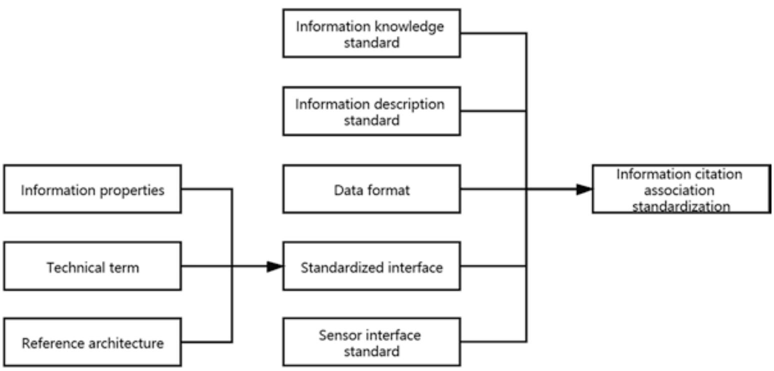

Fig. 2.2 IoT information perception standardization system

At the perception layer, the standardization of sensor interfaces, data types, and formats is the core of standardization.

2.3.1.1 Sensor Interface

At present, among the existing types of sensors, including digital signal sensors, analog signal sensors, pulse signal sensors, and so on, a number of different sensor interfaces exist, and they are not entirely compatible with each other. Therefore, the standardization process of IoT should investigate and analyze the needs of the applied areas; summarize the sensor system, type, and interface mode; and develop a unified sensor interface standard. The commonly used analog and digital interfaces include 4–20 mA, 0–5 V, SPI, I2C, RS-232, CAN, RS-485, and other signal access sensors. To achieve standardization at the sensor level, different types of sensors must be classified and accessed through different information collection channels of the sensing device, and the standardized information can be relied on to form a unified format.

2.3.1.2 Data Types and Formats

Multiple types of sensors from different sources are adopted by IoT systems, and sensor data types and formats are diversified as a result. The sharing information is completed through the standards of sensor data exchange, terms and definitions of automatic identification technology, and other standards.

At present, the commonly used data types include audio, video, image, text, etc. The encoding of data and the compressed data formats include MPEG, JPEG, ASN. 1, XML, and so on. The standardization of the perception layer is, at the same time, the standardized classification, identification, and application of the different types of information. By differentiating data types and formats, formulating clear interface definitions and data specifications, avoiding data mismatch in different sensors and application scenarios, and improving the application efficiency of the sensing layer, ISO and IEC have formulated many standards and completed the terms and definitions of sensor automatic identification technology in 2016. There are also a large number of organizations engaged in sensor data exchange, such as TransducerML, SensorML, IRIG, CBRN, EXDL, and TEDS.

2.3.1.3 Information Identification

Standardized information identification will be the root of IoT standardization. Only when different information are linked through standardized identification can they play major roles in different application systems and generate information value.

The information identifier of the perception layer includes sensor device identifier, information source identifier, information type identifier, device type identifier, information identifier, information type identifier, application type identifier, etc. The standardized identification of such information has passed through some existing standards (such as OID, URI, and so on). In recent years, China has also been pushing its standards to go global. For example, on January 17, 2003, the National Unified Code for Products and Services of China (NPC) standard was officially promulgated. Called *GB 18937-2003 National Unified Code for Product and Service Compilation Rules*, the standard is positioned as a mandatory national standard.

2.3.1.4 Standard Instance of Perception Layer

RFID-Related Standards

ISO/IEC 15459 series defines the registration procedure, general rules, single transportation unit, single product and product packaging, single returnable transportation item, and unique identification of groups.

ISO/IEC 15963:2009 describes a numbering system that can be used to identify RFID tags.

ISO/IEC 18000 series provides different definitions of unique frequency range for various RFID technologies; hence, users can select appropriate equipment types according to their needs.

ISO 6346:1995, ISO/TS 10891:2009, ISO 10374:1991, and ISO 18185 series provide definitions for the encoding, communication, and application of RFID electronic seals for freight containers. These methods ensure that RFID tags attached to containers can operate in a variety of environments. These standards are critical to the integration of supply chain information.

ISO 17363:2013, ISO 17364:2013, ISO 17365:2013, ISO 17366:2013, and ISO 17367:2013 standards relate to RFID applications in supply chain management. These standards define the technical aspects and data hierarchies of the information required at each level of the supply chain.

ISO/IEC 29143:2011, ISO/IEC TR 29172:2011, ISO/IEC 29173-1:2012, ISO/IEC 29175:2012, ISO/IEC 29176:2011, ISO/IEC 29178:2012, and ISO/IEC 29179:2012 standards include standards related to mobile AIDC and mobile RFID and can capture data in a flexible manner.

Design Standards for Smart Sensors and Sensor Networks

ISO/IEC 29182 series provide a sensor network reference architecture (SNRA), which can help users develop sensor networks.

ISO/IEC 20005:2013, ISO/IEC 30101:2014, ISO/IEC 30128:2014, ISO/IEC/IEEE 21450:2010, and ISO/IEC/IEEE 21451 standard are used to create smart sensor networks.

These standards cover such topics as collaborative information processing, smart grid systems, and smart sensor interfaces. By applying the above standards, users can build more reliable and intelligent sensor networks.

2.3.2 Standardization of the Transmission Layer

The network layer is mainly responsible for the access of information-aware data communications and the transmission and exchange of network communications. International standards organizations that are focused on the communication network technology include 3GPP and 3GPP2. More specifically, the two study the standardization of M2M service based on the demand of mobile network.

According to the existing standards, the communication and network standards of the basic perception layer platform are divided into four layers: physical layer, MAC layer, network layer, and backbone network access layer.

2.3.2.1 Physical Layer

The physical layer defines the method for raw data transmission between physical devices on the perception layer. According to the different application requirements of the perception layer, the technical methods included in the physical layer slightly differ. The methods generally include the transmission frequency, modulation method, short-range communication strategy, long-range communication strategy, low-rate transmission, and high-rate transmission. Perception layer devices can be interconnected in either wired or wireless means. Many existing wired and wireless communication standards are relatively mature, including RS-232, RS-485, I2C, SPI, HFC, CAN, Ethernet, etc.

Among them, RS-232, RS-485, and CAN are the most commonly used standard communication interfaces in agriculture. Let us take CAN (Controller Area Network) as an example. Developed by the German-based company Bosch, known for the R&D and production of automotive electronic products, CAN is a serial data communication protocol invented to enable the data exchange between modern automotive control and test instruments. Eventually, CAN became an international standard (ISO 11898). In North America and Western Europe, the CAN bus protocol has become the standard bus for automotive computer control systems and embedded industrial control local area networks and is increasingly used in agriculture. For instance, the agricultural temperature monitoring system is based on CAN bus (Gao et al. 2016).

2.3.2.2 MAC Layer

The MAC layer ensures the logical connection between the devices in the sensing layer and realizes the communication between devices through addressing and channel access control. In order to make up for the unreliability of data transmission in the physical layer, the MAC layer also provides such services as flow control, error detection, and error control, thus ensuring the reliable transmission of data between devices.

Compared with other network entities, the perception layer of IoT is limited by energy, communication, storage, and computing capabilities, which is why the standard of the MAC layer must allow higher energy efficiency and less data interaction. Some existing MAC layer protocols do not take these restrictions into consideration; thus, they cannot be effectively applied to the IoT perception layer. Depending on research on the scalability of existing MAC layer protocols (such as CSMA/Ca, dynamic DMA, and S-MAC), device sleep strategy, channel access control technology, flow and error control technology, multiplexing technology, and the applicability of existing MAC layer technology in the IoT can be improved.

2.3.2.3 Network Layer

The network layer, located above the physical layer and MAC layer in the IoT communication, is equipped with the functions of flow control, tolerance control, relay routing, and route selection of the whole network. In the process of network layer standardization, the key standardization technology still lies in the transmission protocol, resolution algorithms, and automatic identification and mapping of address.

2.3.2.4 Backbone Access Layer

IoT is characterized by the continuous generalization of "things" and "things" connected networks, that is, small communication LANs are continuously connected with the external LANs, eventually giving birth to something that is based on the Internet, yet transcends the scope of the Internet. The key is to connect small LAN to WAN. At this time, the communication layer needs to access the communication backbone to realize its application. Here, the key to access is to standardize the protocol of access layer. By defining the sending and receiving of gateway, the application program interface, and the data communication format through standardized protocol, the interconnection of standardized backbone network is realized, which plays a decisive role in the realization of various applications in the perception layer of IoT. Depending on wired or wireless means of transmission, the transmission layer standards are divided into wired communication standards and wireless communication standards.

Wired communication standards include Ethernet, ATM, Frame Relay, SDH, FDDI, Fibre Channel, ISDN, VPN, VoIP, Cable/xDSL, BACNet, CAN bus, ControlNet, DeviceNet, Dupline, FF, HART, INTERBUS, LonWorks, Modbus, PROFIBUS, SWIFTNet, Vnet/IP, WorldFIP, CC-Link Industrial Ethernet, RS-232, RS-485, and other different bus technologies.

Wireless communication standards include 2G (GSM, CDMA), 2.5G (EDGE, HSCSD), 3G (WCDMA, EV-DO, HSUPA, EV-DOrA), 4G (EV-DOrB, LTE, WiMAX, UMB, UWB), Bluetooth, HiperLAN, 6LoWPAN, HomeRF, Insteon, IrDA, IRIG, NFC, RFID, WAVE, Wi-Fi, Zigbee, Z-Wave, and other wireless communication technologies.

Compared with wired transmission, the restrictions on energy consumption, communication, storage, and computing power in wireless transmission network are far more inferior. Therefore, wireless transmission network poses greater challenges to the network layer standard, requiring automatic configuration of network information, automatic address resolution between network addresses and physical addresses, and automatic data unit transmission and protocol decoding between points.

2.3.2.5 Transport Layer Standard Examples

IEC 61158 series and IEC 61784 series, used for real-time distributed control, are the standard for fieldbus configuration and configuration files, including basic fieldbus, involving PROFIBUS and PROFINET, P-Net, WorldFIP, INTERBUS, SWIFTNet, CC-Link, HART, VNET/IP, TCnet, EtherCAT, Ethernet Powerlink, Factory Automation Ethernet (EPA), Modbus, SERCOS, RAPIEnet, SafetyNet, and MECHATROLINK.

IEC 62591:2016 (WirelessHART™) and IEC 62601:2015 (WIA-PA), industrial wireless communication standards for process automation, are suitable for industrial measurement and monitoring of wireless network systems. WirelessHART™ is a standard designed for process measurement and control applications to manage real-time operations. Both of the above standards are used for industrial wireless transmission, while the ISO/IEC 14476 series is used to enhance communication transmission protocols and ensure the quality of service (QoS).

ISO/IEC 29180:2012 is used to ensure the security of ubiquitous sensor networks.

ISO/IEC 27033 series are used to ensure network and information security and minimize the risk of information security crisis.

IEC 62443 series are relied on to ensure the safety of industrial automation and control system and to provide comprehensive safety protection.

ISO/IEC8802 series are international standards that relate to the transmission layer, and its applicable scope includes local area networks (LAN) and metropolitan area networks (MAN). LAN is used for micro-wired or wireless transmission in small workplaces, homes, and offices, whereas MAN is connected to many LANs, and both standards are micro-communications.

2.3.2.6 Relevant International Standards Organizations

At present, international standards organizations that are focused on the communication network technology include 3GPP and 3GPP2. More specifically, the two study the standardization of M2M service based on the demand of mobile network. Among the international standards organizations that have carried out systematic research on the general framework of ubiquitous networks, the

International Telecommunication Union (ITU-T) and the European Telecommunication Standardization Institute (ETSI) M2M Technical Committee are the typical international standards organizations. In particular, ITU-T studies the overall architecture from the perspective of ubiquitous network, while ETSI studies the overall architecture from the perspective of M2M (Lang et al. 2019; Yang et al. 2013).

2.3.3 Standardization of the Application Layer

Using the collected data, the application layer forms a dynamic data resource database, which meets IoT-related business needs. IoT-related businesses include those engaged in retail, health, energy, mobility, city, manufacturing, publishing, and services. A large number of standards organizations have formulated application level standards for specific applications, mainly involving application technologies. Different from the standard system in the field of traditional computer and communication that does not involve specific application standards, IoT is dominated by application. In the application layer of IoT, there are quite a number of standards in the fields of intelligent measurement, e-health, urban automation, automobile application, consumer electronics application, and so on.

Application layer standards can be divided into data standards and software framework standards. Specifically, data standards include Object Name Service (ONS)/Physical Markup Language (PML), Next-Generation Telematics Protocol (NGTP), Electronic Device Description Language (EDDL), FDT/DTM, OPC, M2MXML, BITXml, and Open Building Information Xchange (oBIX). Software frameworks include, for instance, DRM, IDM, MDM, SOA, OSGi, and software as Service (SaaS), ArchestrA, and Sedona.

Below are some of the examples of IEC international standards related to the IoT application.

IEC 62453 (FDT): used for the standardization of communication and configuration interfaces between field devices and host systems. The device can be configured, operated, and maintained through the user interface.

IEC 61804-3, IEC 61804-4, IEC 61804-5, and IEC 61804-6 (EDDL): used for the description of the digital communication characteristics of intelligent field instruments and equipment parameters. EDDL technology, a communication protocol, enables host system manufacturers to create a single engineering environment that can support multiple devices from any vendor.

2.3.3.1 Overview of Agricultural IoT Standards

According to the definition of IoT mentioned above and the definitions of standards, standardization, and standard systems, we could determine the definition of agricultural IoT standards – the standards of agricultural IoT are the standards and basis for summarizing the scientific and technological achievements of IoT technology in the specific application of agricultural production, operation, management, and service and are approved by the relevant department of agricultural standards or the relevant professional committee. Moreover, the standards of agricultural IoT are issued in the prescribed form, recognized in the relevant fields, and followed jointly by the relevant parties.

Recent years witnessed remarkable progresses in the construction of agricultural IoT. Gradually, countries and regions around the globe have started with the application and demonstration programs of agricultural IoT. These projects explored extensively for the research of key technologies of agricultural IoT and for the establishment of the standard system. However, as the construction of agricultural IoT accelerates, a number of problems have arisen, thus limiting its further development. For example, due to the lack of a unified and standardized concept for agricultural sensor standards, the interface functions of agricultural sensors produced by different manufacturers significantly differ, and it is difficult to integrate them into an agricultural IoT application system. Furthermore, owing to the lack of perception data storage and standardized description of application, it is difficult to share data between different IoT application systems, and because of the lack of standards for IoT in agricultural production, including crop farming, facility horticulture, livestock farming, and aquaculture, IoT systems established in different units and regions are not compatible, and data and equipment information are not universal (Shen and Yang 2015).

These problems reflect the weak links in agricultural IoT standardization. The lack of relevant standards makes it difficult to integrate the sensing layer devices of agricultural IoT. By the same token, the information transmitted by the transmission layer is difficult to adapt to networks with different topologies. The diverse types of services and methods provided by the application layer make the construction of agricultural IoT quite challenging, and costs cannot be effectively controlled. Therefore, in order to promote the rapid, unified, and standardized development of agricultural IoT, it is necessary to strengthen the construction of agricultural IoT standards. By building an IoT system for agricultural applications, such as field agriculture, facility agriculture, orchard agriculture, and aquaculture, different sensing devices can be integrated with applications, different sensing transmission network architectures can be seamlessly connected, and different sensing services can be coordinated and unified to ensure the healthy, orderly, rapid, and scientific development of agricultural IoT (Lee 2008).

As the basis for standardizing the application system of agricultural IoT, the standards of agricultural IoT are also fundamental to realizing the sharing of perceived data and services of agriculture. Therefore, agricultural IoT standard systems play an extremely important role in pursuing related technologies of agricultural IoT.

The standardization of agricultural IoT is a process of formulating, issuing, and implementing the standards of agricultural IoT for achieving unity. The standard system of agricultural IoT is an organic whole composed of several standards documents that are interactive and interdependent, and they also feature specific functions. There are two standard systems of agricultural IoT, namely, basic general standard and industrial application standard. Standardization constitutes the basis for the integration of key technologies of agricultural IoT, the premise for standardizing the R&D and production of relevant equipment, and the foundation for standardizing the application system. It is the key to the sharing of agricultural data and services, especially to the interconnection of different systems, and the use of applications.

2.3.3.2 Standard Systems of Agricultural IoT

The content of standard systems of agricultural IoT can be divided into two categories: the basic general standard of agricultural IoT and the standard of industrial IoT. The basic general standards of the agricultural IoT include the general standards of agricultural IoT, the perception level standard system, the network level standard system, the application level standard system, and the common key technology standard system. The standard system of IoT in agriculture covers such aspects as crop farming, aquaculture, and livestock farming. Figure 2.3 offers an illustration of the specific structure of the system (Gao 2017).

The standard system of the agricultural IoT is relatively complex. In fact, the system can be constructed from six levels – the overall level, the perception level, the network level, the processing level, the application level, and the common key technology standard system. The standard system of agricultural IoT covers architecture standards, application requirements standards, communication protocols, identification standards, security standards, application standards, data standards, information processing standards, and public service platform standards, each of which may also involve technical standards, protocol standards, interface standards, equipment standards, test standards, interworking standards, etc. (Zhang and Zhang 2019).

2.3.3.3 Standardization of Agricultural IoT Application System

The application system of agricultural IoT includes rich contents. Generally speaking, it includes the IoT management of crop farming, livestock farming, and aquaculture. Among them, crop farming is divided into two kinds: field agricultural IoT and facility agricultural IoT. In actual practice, there will be more branches of application, and the subsystems may also have their own industry-specific and region-specific characteristics. For example, in the application of IoT in crop farming, the measures adopted for different growth stages are completely different, the IoT application system in seedling raising process, the IoT system in field growth process, etc. Moreover, crop farming in different regions and varieties significantly differ. Therefore, the standardization of agricultural IoT application system mainly features standardized application models from the macro perspective (refer to Fig. 2.4 for the standardized water product networking system in crop farming).

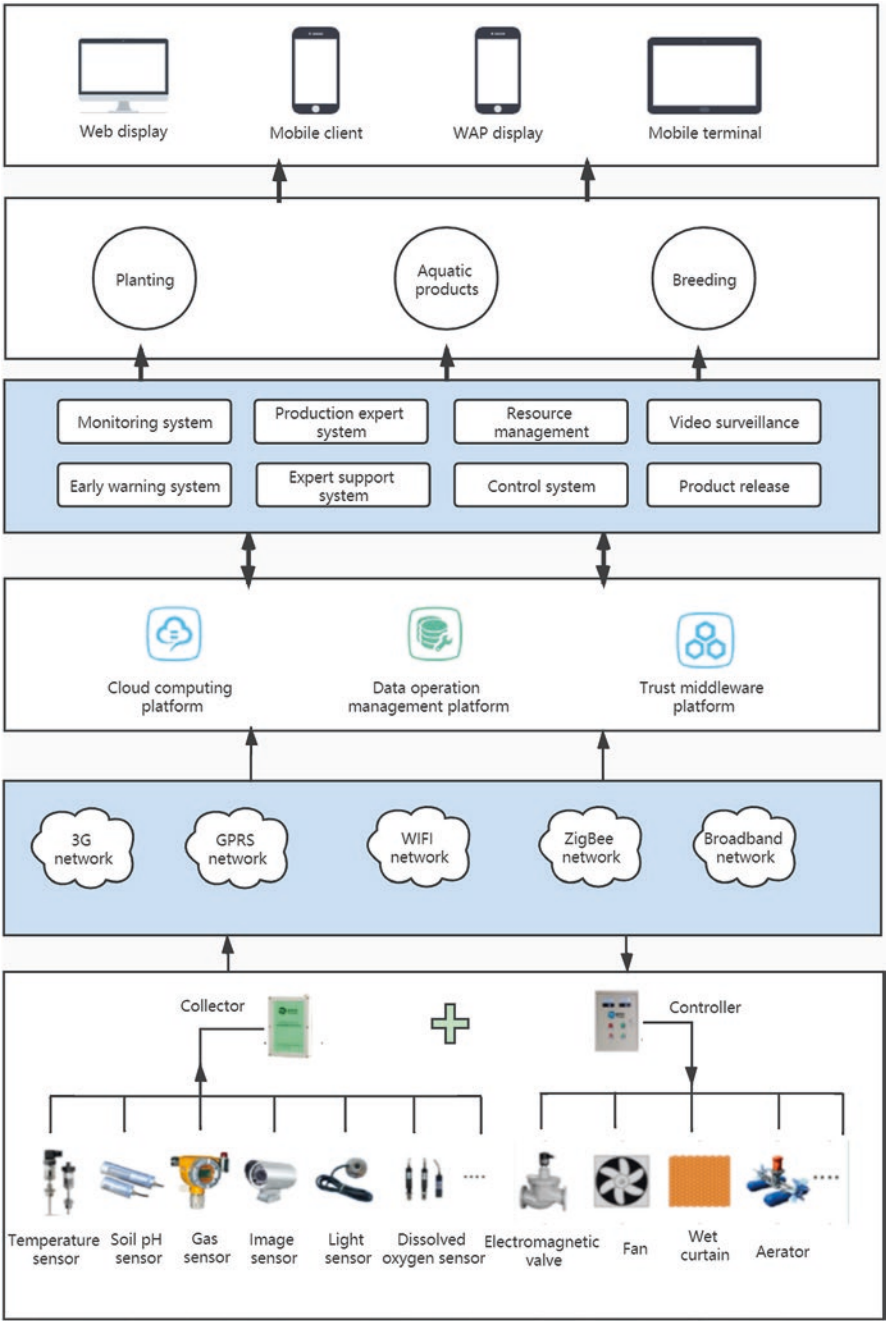

Fig. 2.3 Standard system of agricultural IoT

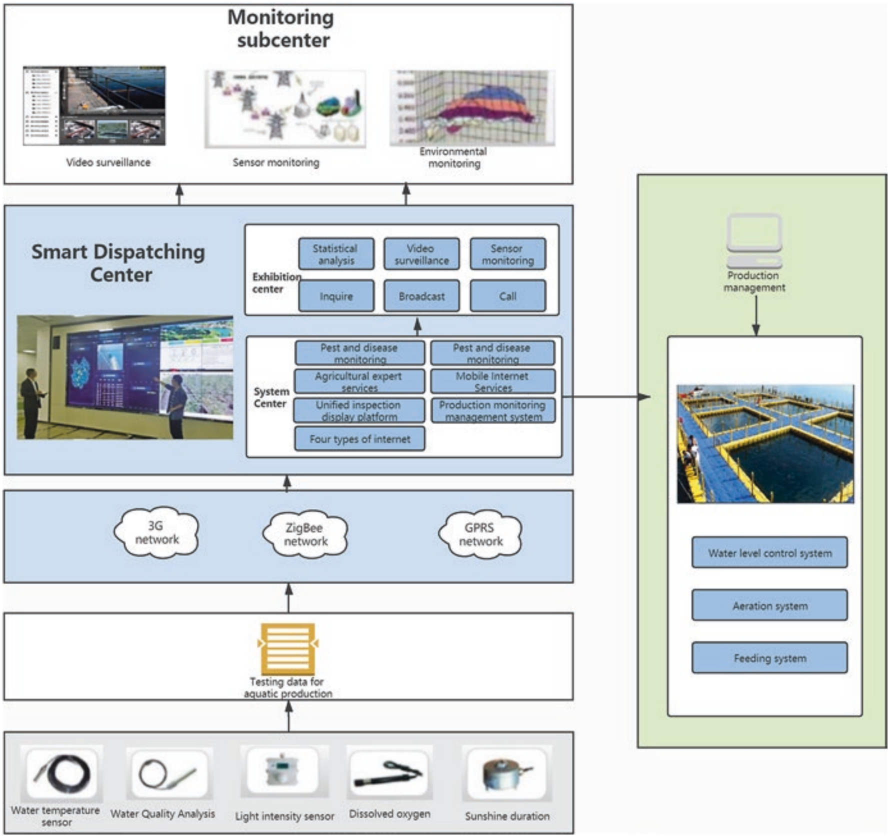

Fig. 2.4 Standardization structure of IoT system in aquaculture

In the aquatic product networking, water environment information is mainly obtained through various water quality sensors, and the water environment is thoroughly adjusted in combination with aquaculture technology to create the optimal environment for aquaculture, thereby making the industry efficient and safe. However, the application of IoT standards in the breeding process of each species or at different stages still demands extensive research. Similarly, in livestock farming, the perception system includes not only sensor data but also sound, image, and video information, as shown in Fig. 2.5.

The standardization of agricultural IoT system has yielded fruitful results in the basic technology layer, but the progress in the application layer remains slow. In general, the technical standards for agricultural IoT are steadily moving forward. The following are some of the more prominent progresses delivered so far.

- The standards of agricultural IoT and those of IoT in general are consistent.
- IoT is based on the extensive application of object coding technology and sensor technology. Its core technology is still information perception and coding identification and automatic identification and network technology. Therefore, in building the standardization system of agricultural IoT, one should attach greater

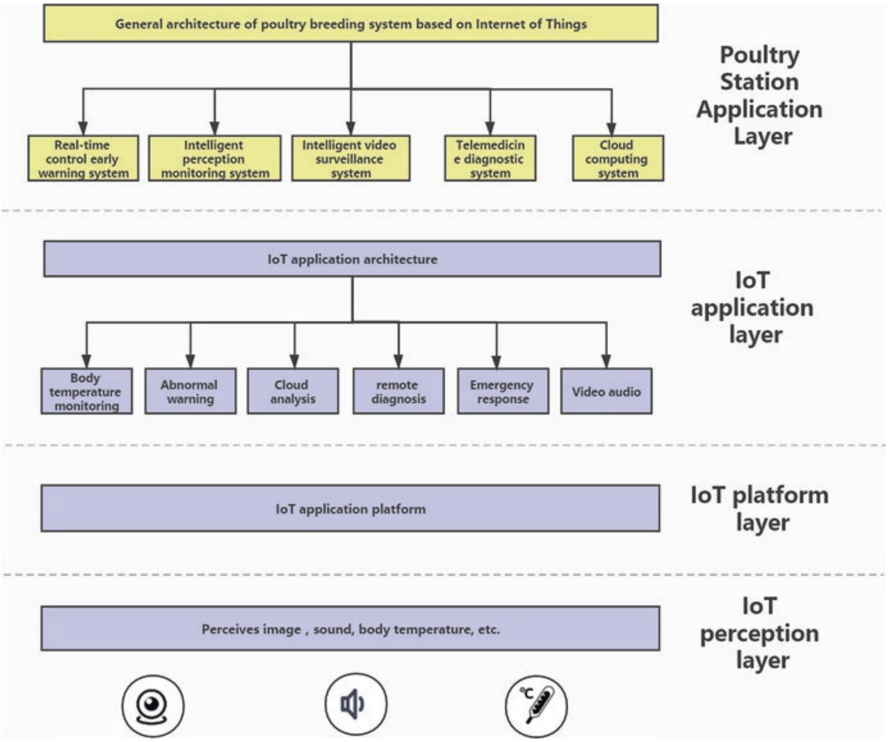

Fig. 2.5 Application of IoT standardization system in livestock and poultry breeding

importance to the standardization of information perception, such as information identification, information definition, and information format.

- The major contents of the standardization of agricultural IoT include the function, performance, and interface standards of agricultural sensors and identification equipment, data transmission and communication protocol standards, agricultural multi-source data fusion analysis and processing standards, application service standards, construction specifications of agricultural IoT projects, etc.

2.4 Summary

This chapter elucidates the concepts of standards, standardization, and standard system and summarizes the concept of the standardization system of the agricultural IoT. Finally, it lays out a brief introduction of the existing standards and standard construction specifications involved in the application of the sensing layer, transmission layer, and application layer of agricultural IoT, including crop farming, facility gardening, livestock farming, aquaculture, and agricultural products logistics. After reading the chapter, readers are expected to build an overall understanding of the standardization system of agricultural IoT.

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Chapter 3
Data Communication and Networking Technologies

Qin Zhang, Yong He, Pengcheng Nie, and Shupei Xiao

Abstract An agricultural IoT system connects many physical devices, both in office or in field, to perform effective farming operations supported by collecting, processing, and sharing data, often automatically, in real time. To provide such functionalities, both the data communication and networking technologies play an essential role. This chapter provides some fundamental knowledge of data communication and networking technologies and also uses a few examples to explain how some of commonly seen networking technologies are being used in agriculture to support field operations.

Keywords Wired and wireless communication · IoT networks · Zigbee · LoRa · Narrowband IoT

3.1 Introduction

Agricultural IoT technology connects field machines to computing devices for seamlessly supporting more effective data-driven farming through integrating sensing, data processing, decision-making, and automated control technologies in an IoT platform (Villa-Henriksen et al. 2020; Talavera et al. 2017). Data communication, either wired or wireless, provide the base for networking all interrelated devices seamlessly in performing the operation. The “data” here is a general term and could be either analog signals outputted from some analog sensors, digital signals communicating between computing devices, imaging signals from camera or imaging sensors, or voice signals from recorders, phones, or even TVs, depending on the type of devices being connected in an IoT. The basic function of data

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communication in an agricultural IoT system is to transmit data instantly, errorlessly, and reliably for having the field work done effectively and productively. For instance, when a networked agricultural sprayer is applying nitrogen on the field, the IoT platform will need to transmit the sensed sprayer location data in operating field to a prescription maker being implemented on an in-office computer and then deliver back an appropriate prescription for the location to individual nozzle controllers on the sprayer for performing automated variable rate nitrogen application.

Data communication in agricultural IoT systems could include different technologies, such as analog or digital communication technologies, program-controlled data exchange technology, networking technology, broadband IP technology, access network and access technology, and many more. In an IoT system, the networked devices could receive input data and/or send output data via either some type of wires or some types of wireless accessing points. Therefore, it is essential to some fundamental knowledge on wired and wireless technologies for data communication. Similarly, as IoT composing devices are connected in an Internet environment, it implies they are connected using some types of network technologies, so that some background information of networking technologies is also very important for understanding agricultural IoT technologies and adopting it to the production. For sharing data at appropriate scale, an agricultural IoT could be built on a regional network, a local area network, a corporate internal network, or even a home/personal network (Jesus et al. 2012; Qu 2013).

As aforestated, the convergence of sensing, computing, and communication technologies for automated agricultural applications has led to the creation of agricultural IoT systems. The backbone of an agricultural IoT system is secure, reliable, and fast data communication among connected devices, which demand the adoption of communication technologies (Zhang and Ehsani 2006). This chapter mainly introduces two topics on data communication, including wired and wireless data communication and networking technologies. To present relevant information easily to follow and understand without extensive technical details, we will start with a brief introduction on wired and wireless data communication (Sect. 3.2), followed by networking technologies with a few examples of agricultural IoT applications (Sect. 3.3). Section 3.4 will provide a brief summary on these introduced technologies and their suitability for agricultural applications.

3.2 Wired and Wireless Communication Technologies

As implied by their names, the major difference between wired and wireless communication technologies is that the former sends data through a wire of some kinds, while the latter does not need a wire but uses some forms of electromagnetic waves. Some good examples of both categories are landline telephone for wired communication and cellphone for wireless communication. It should be clearly understood that the wireless communication transmits data wirelessly only inter-device, not intra-device. Both technologies have a few characterized advantages over the other in different aspects, where one of the most distinguishable for each is that the wired communication has a higher immunity to outside interference, while the wireless communication could connect devices in all locations without the limitation of physical wiring. This section will provide a brief overview on both technologies.

3.2.1 Wired Data Communication Technologies

3.2.1.1 Overview of Wired Data Communication Technology

Transmitting data over wires and cables is defined as wired data communication, and it is the oldest method and the basis for all data communication and by far the most common and matured technology for data communication. The main advantages of wired data transmission include high security, i.e., physical connection between devices making it very difficult, if not impossible, to eavesdrop or tamper with the data from outside; ease of use, i.e., simply needs to plug in to add a device or unplug to remove it; long distance, i.e., can connect devices far away using proper wiring method; high speed; and reliability. However, it also has some common disadvantages, such as cost and complexity, difficult to relocate or add devices, and requiring power supply to keep it working (Mocrii et al. 2018). There are three types of wires, i.e., twisted pair, coaxial, and fiber-optic cables, being widely used for data communication applications, including for IoT applications.

In an IoT all data are sent or received by some connected devices, such as computers, display monitors, data storage, data transmitters, sensors, controllers, and actuators. Among those, some could directly communicate with the computer, and others will need some types of bridging device to communicate with computers. It is common to call devices which could directly communicate with computers the peripherals, and the others computer-controlled devices. Normally, data communication between the computer and its peripherals can be achieved in either parallel or serial mode, and between computers and their controlled devices, is mostly, if not always, carried in serial mode. The difference is that the serial data transmission sends data bits one after another over a single channel, while the parallel data transmission sends multiple data bits at the same time over multiple channels. As the data communication we are interested in agricultural IoT is mostly for those computer-controlled devices, we will focus on serial mode data communication in this book.

3.2.1.2 Wired Data Transmitting Cables

Twisted Pair Wires

As aforementioned, an IoT system could use three different types of cables: twisted pair, coaxial, and fiber-optic wired data communication. A twisted pair (TP) cable is made of one or more pairs of insulated copper wire twisted together for minimizing electromagnetic radiation and resisting external interference. It also helps to reduce interference with adjacent wires or other operating electrical devices (Insam 2003). In theory, the more twists per unit length a cable has, the better isolation performance it could achieve. On the other side, such increase in twist will result in a higher capacitance which in turn will require more power to transmit the data, as well as cause an increased signal attenuation especially in high-frequency range. There are two types of twisted pair cables, unshielded twisted pair (UTP) and shielded twisted pair (STP), with the latter having a layer of aluminum foil wrapping the wire pair for additional isolation. The impedance of typical TPs is at the order of 100–150 Ω.

TP wires use a voltage differential mode to transmit signals: a positive pulse fed to one wire is matched by a corresponding negative pulse on the other to generate equal but opposite magnetic fields for cancelling each other out for maintaining a zero total radiation field around the pair. To improve the performance of noise cancellation, the twisted pair often have two wires at different lengths, as well as twisted at different rates. The length difference between the two wires could be 5% or more. TPs are often used in bus topologies to connect computers and other devices using one single cable to a hub. The signal sent from one station to the hub could be redirected to all the other stations on the network. TP cables are classified by categories according to rated speed.

Coaxial Cables

Coaxial cable is a type of electrical cable fabricated by running an inner conductor inside a concentric outer conductor separated by a layer of dielectric insulator. The term "coaxial" refers to the inner and the outer conductors sharing a geometric axis. Many coaxial cables also have a protective outer insulator and/or jacket. There are many types of coaxial cable available in the market, with four types most commonly used being (1) flexible coax, most commonly used type with a braided outer conductor of extremely fine wires for providing the flexibility; (2) semirigid coax, using a solid tubular metallic outer conductor similar to a pipe for providing a uniform characteristic impedance and excellent shielding; (3) triaxial coax, using two layers of outer conductors separately for signal and earth ground to achieve the best noise immunity and shielding performance; and (4) dual coax, consisting of two individual coaxial cables surrounded by a common outer jacket.

Coaxial cable is commonly used to transmit high-frequency electrical signals with low losses. During the transmission, a coaxial cable carries equal but opposite currents in both the inner and the outer conductors to confine all propagation of electromagnetic waves inside the cable. This is the distinguished advantage of coaxial cable over TP wires. Coaxial cables were very popularly used in networking applications in the early days, especially those cheap and readily available video and radio-frequency coaxial cables. In coaxial cable connecting, all nodes are connected via a single backbone to link all stations under a bus topology. A resistive 75 (or 50) Ω terminator R is used at each end of the cable to absorb all reflections and make all the devices connected in the line look like just a purely resistive load of $R/2$ Ω. The voltage generated on the line is of the order of half a volt for a typical

Ethernet network which allows receivers to use dynamically adjustable threshold sensors to determine zero crossings and also to detect voltage overloads caused when two or more station transmitters are attempting to drive the line together for avoiding signal collision. Normally, the outside of the shield is kept at ground potential, and a signal carrying voltage is applied to the center conductor. However, the coaxial cable shield connection is normally grounded at only one point; network adapters must therefore incorporate isolation hardware to float all the power supplies.

Fiber-Optic Cables
A fiber-optic cable is fairly similar to coaxial cable in appearance, but with its communication core made of thin fiber of glass down in which light pulses can be sent. Fiber-optic cables are normally fabricated by having a glass core in the center and surrounded by several layers of protective materials. It is in general free of electrical interference problems and highly resisting to the effects of moisture and lighting. As it has much higher bandwidth than coaxial and TP cables and could transmit data over longer distances, fiber-optic cable is designed for long-distance, high-performance data networking and telecommunications. The cost of fiber-optic cabling is comparable to copper cabling; however, it is more difficult to install and modify. Today, fiber-optic cables are commonly used in much of wired data communication in IoT systems, and a more detailed introduction and discussion will be covered in a separate section (Sect. 3.2.1.4) later in this chapter.

3.2.1.3 Fieldbus Technologies

As a kind of wired communication technology for interconnecting devices at the bottom of automation, fieldbus is also widely used in field communication networks and control systems. Fieldbus is a digital, multi-branched, and bi-directional transmission communication network to connect multiple devices supporting automated field operations. To meet the special needs of different applications, there are a few kinds of fieldbus technologies that could be adopted. Some fieldbuses are more suitable for mobile applications than others. Limited by the scope of this book, this section will briefly introduce three types of fieldbuses often seen in agricultural applications, i.e., Serial Peripheral Interface (SPI) bus, Modbus, and CAN bus.

Serial Peripheral Interface (SPI) Bus
Serial Peripheral Interface (SPI) is one of the most widely used interfaces for serial mode of data transmission and often used to connect microcontrollers and peripheral devices to support synchronous exchange of information in a serial manner. A SPI bus is constructed by either three-wire or four-wire design, with a four-wire design being more popularly used: a serial clock (SCK) line, two data lines of master out slave in (MOSI) and master in slave out (MISO), and a slave select (SS) line. The use of SPI bus is particularly convenient in a microcontroller system with fewer SPI slave devices and no bus expansion capability. SPI devices can work in both master and slave modes, with only one of the SPI interfaces being served as the

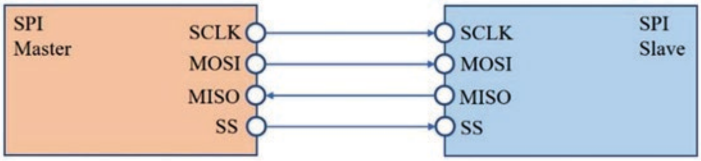

Fig. 3.1 Typical connection between a master and a slave device using SPI serial interface

master in a network while multiple ones as slaves. The device that generates the clock signal is called the master. Data transmitted between the master and the slave is synchronized to the clock generated by the master. Figure 3.1 shows typical SPI bus communication between master and slave devices.

In a SPI serial expansion system, if a slave device is responding to only input (such as a keyboard) or output (such as a display), a data output (MOSI) or a data input (MOSI) can be omitted, and a three-wire system can be used in such applications. When devices of different serial I/O ports are to be connected using a SPI bus as slave devices, it must have a chip selection terminal with its output pin connected to MISO line. In addition, a high-impedance state from invalid chip selection ought to be maintained to ensure normal operations of other SPI devices would not be affected.

Typically, a master SPI can write data to or request data from several slave devices and call it a multiple slave selection configuration which is often treated as the standard SPI arrangement. Figure 3.2 illustrates such a standard arrangement with one master device and three independent slave devices that share common data lines by enabling the device via setting the slave select line of the corresponding device to logic low. In normal operation, individual slave devices should not be enabled simultaneously as the data returned to the master would be corrupted by driver contention between the MISO lines. However, in some applications, if the master wants to send the same data to more than one slaves but no data be required returning to the master, then those slaves could be enabled simultaneously.

In some applications, the slaves are configured in such a way that all slaves share a common slave select line and data is shifted out of the master into the first slave and then propagates from one slave to the next in sequence with all slaves receiving the same SPI clock at the same time. Figure 3.3 illustrates the system arrangement for such a data cascading configuration which is often called daisy chain configuration. In this configuration, the data propagates down the line until the last slave in the series which can then use its MISO line to send data to the master device. The number of clock cycles required to transmit data is proportional to the slave position in the daisy chain.

There are a few other SPI system configurations often seen in different applications. SPI bus interface has been around for decades and gained a very broad application in connecting digital devices to microcontrollers. It can be expected that it will remain popular for a foreseeable future as it is a versatile and straightforward serial communications interface that is excellent for certain applications.

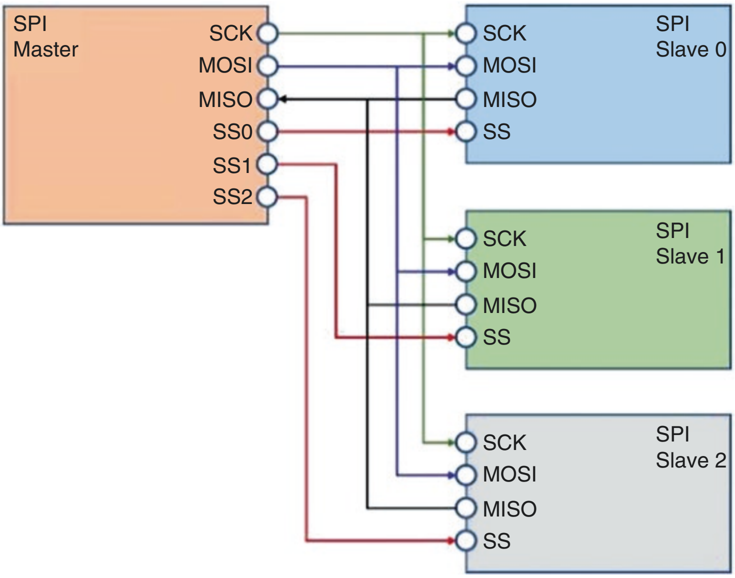

Fig. 3.2 An illustration of multiple slave select configuration using SPI serial interface

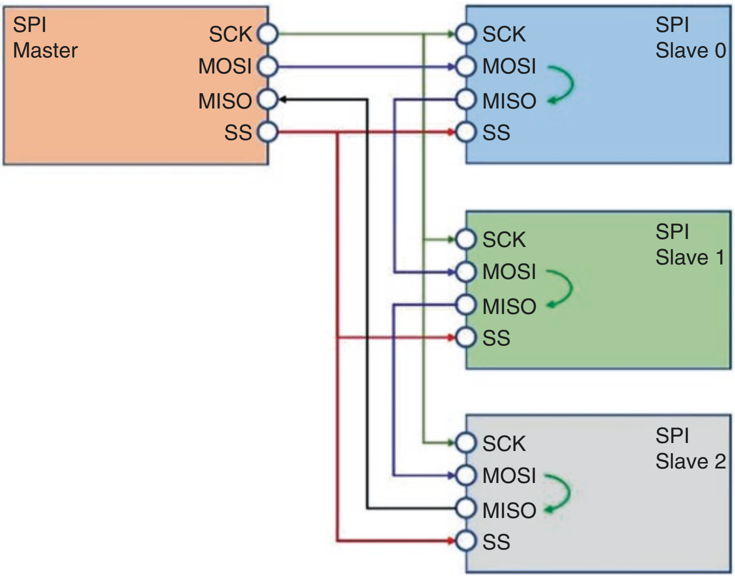

Fig. 3.3 An illustration of daisy chain configuration using SPI serial interface

Modbus

Modbus is an open serial protocol standard created in the late 1970s for communication among programmable logic controllers (PLCs). It is a widely accepted serial level protocol due to its ease of use and reliability. Modbus is often used to connect a supervisory computer with a remote terminal unit (RTU) in supervisory control and data acquisition (SCADA) systems. Modbus protocol primarily uses an RS-232 or RS-485, an enhanced version of RS-232, serial interface for communications, and the standard Modbus port is an RS-232-compatible serial interface with today's commonly used RTUs over RS-485. Such an interface makes Modbus supported by almost every commercial SCADA, HMI (Human-Machine Interface), and OPC (Open Platform Communications) servers in the marketplace. By the same token, Modbus protocol can easily incorporate with Ethernet TCP/IP (transmission control protocol/Internet protocol) in an integrated communication protocol which makes it easily achieve seamless communication between all types of networks.

Like SPI system, Modbus protocol is derived from the master-slave architecture which makes a device operating as a master poll one or more devices operating as slaves. In this master-slave communication technology, only the master device (client) can initiate a transmission (query), and slave devices (servers) would respond accordingly based on the data provided by the master. There can only be one master device on a network with every device (master and slave) having a unique address of its own. The master device can communicate with slave devices individually or to all using a broadcast mode. When communicating in an individual mode, the slave could return a message as a response; and when in a broadcast mode, the slaves would be unable to respond. It is noteworthy that slave devices cannot communicate with each other in Modbus protocol. The query from the masterpiece must follow a certain format: device address (or broadcast address), function code, data to be sent, and error detection field. The slave response is also specified in a format of device address, function code, data to be returned, and error detection field. If the slave cannot execute the command sent by the master, it will generate an error message and send it back to the master as a response. In messaging, the Modbus protocol obeys the master-slave principle, even though the network communication method (such as the Internet) could be peer-to-peer. If a controller sends a message, it only acts as the master and expects a response from the slave. Similarly, when the controller receives a message, it will establish the slave response format and return it to the sending controller (Tian 2018).

Modbus protocol is actually an application-layer communication protocol that is located at the seventh layer in the Open Systems Interconnection (OSI) mode. Modbus offers the service specified by the function code through the request/response mode. Modbus function code is included in the request/response protocol data unit (PDU). Modbus can be used in TCP/IP of Ethernet, asynchronous serial transmission of multiple media (wire, fiber, wireless, etc.), and Modbus+ and other occasions. Figure 3.4 is an illustration of Modbus communication layer (Chen et al. 2017). The main advantages of Modbus protocol are its flexibility and its readiness for implementation.

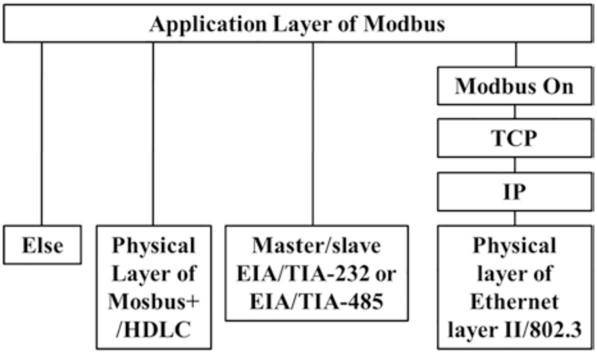

Fig. 3.4 Communication layer of Modbus

A PDU consists of a function code and the data to be transmitted in message frame of this serial communication protocol, while an ADU (application data unit) includes the address in front of the PDU and an error code at the end of the message frame. Such a message frame provides Modbus protocol the flexibility of transmitting data between different network environments. For example, when Modbus protocol is being used in a master-slave mode, it allows only one master station to initiate a communication for driving multiple slave nodes connected to the same bus, while those slave stations may need responding differently to communication requests from the master. If the master requested communicating individually with specific slave, it would need having the address information of the slave to be communicated, as well as may need getting feedback from the slave if error occurs. If it were operating at a broadcast mode, then such additional information is not necessary. This design of message frame structure provides the needed flexibility.

Modbus protocol defines four types of registers to distinguish their attributes in serial data transmitting, coil, a 1-bit read/write register for controlling discrete outputs; discrete input (or status inputs), a 1-bit read-only register used as input; input register, a 16-bit read-only register used for input; and holding register, a 16-bit read/write register for a variety of things including inputs, outputs, configuration data, or any requirement for "holding" data, and is changeable for different applications. A single segment in Modbus protocol allows to have up to 65,536 data units, each correspondingly allowing read/write operations. In addition, the size of the data operation length can be defined according to the operation code that is delivered, and the length of the data operation can reach the maximum value of the data area. Modbus uses a "big-endian" encoding method for addresses and data communication, i.e., when the value of the data is greater than 1 byte, the MSB (most significant bit) will be sent first.

Though the data to be operated by Modbus needs to be stored in the memory, the association between the data addresses and the physical addresses on these memories does not directly correspond, and one only needs to connect the addresses on the memory to the corresponding data. If the memories of devices vary from one another, the method of allocation would also differ depending on the device (Lv 2011).

CAN Bus

CAN bus, standing for Controller Area Network bus, was originally developed by Bosch in the mid-1980s to connect in-vehicle embedded systems using a pair of signal wires (Zhang and Ehsani 2006). In 1990, Mercedes-Benz released the first car using CAN bus, and now almost every new car is equipped with a CAN bus network. CAN bus has been incorporated into international standards since 1993. Currently, there are few CAN bus standards documented by the International Organization for Standardization (ISO), such as ISO 11898 for applications up to 1 Mbps and ISO 11519 for applications up to 125 Kbps (Kuang et al. 2011). Based on these standards, each CAN message has an identifier which is either 11 bits (CAN specification 2.0 A) or 29 bits (CAN specification 2.0 B). In the United States, the automobile industry has led the effort to develop a CAN communications standard through the Society of Automotive Engineers International (SAE) in the early 1990s which resulted in a compatible standard (SAE J1939) for vehicle bus. To address challenges in agricultural and forestry applications, ISO has published a standard specially for agricultural equipment (ISO 11783: Tractors and Machinery for Agricultural and Forestry-Serial Communications and Communications Data Network standard) to meet the needs for electronic communication between tractor and implements, between components within tractors, and within implements which allows tractors to be able to connect to implements made by different manufacturers. To distinguish this agricultural machinery-specific CAN protocol from others, it is often called ISOBUS.

Many network protocols can be described using an ISO seven-layer OSI (Open Systems Interconnection) model, and CAN protocols define the data link layer and part of the physical layer in this OSI model (Fig. 3.5). In addition, the standard allows users to define or specify an application layer making it suitable for different applications. A couple examples are CAN open defined by CiA (CAN in Automation) and DeviceNet by ODVA, Inc.

Defined by the CAN specification, a data link layer provides two functions of logical link control (LLC) and medium access control (MAC). The former manages the overload control and notification, message filtering, and recovery management functions; and the latter performs the data encapsulation/decapsulation, error detection and control, bit stuffing or destuffing, and the serialization and deserialization functions.

The primary function of the physical layer is to achieve signal transmission between devices, to convert various complex information into physical signals (usually electrical signals or optical signals) that can be transmitted, and to transmit these signals to other devices. This is done through physical signaling (PS), physical medium attachment (PMA), and medium-dependent interface (MDI). Among the three, PMA and MDI are not defined by CAN specifications. The only one defined by CAN specification is PS which performs bit encoding, transmission, reception and decoding, as well as timing and synchronization. PS performs bit encoding,

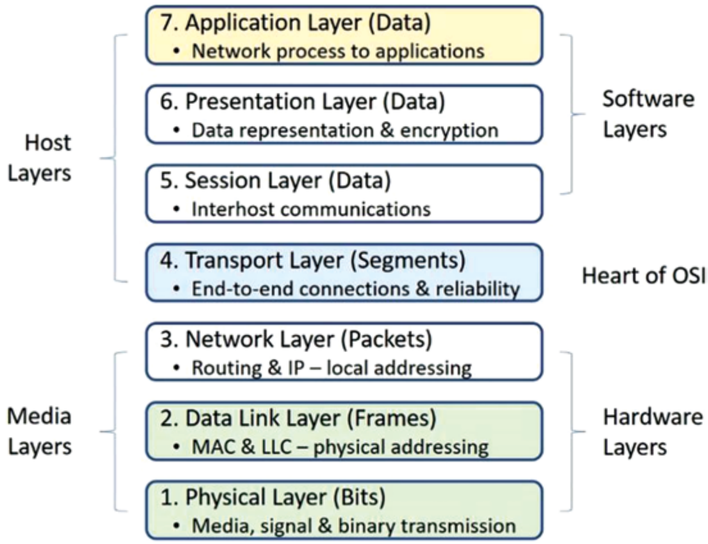

Fig. 3.5 Structure of ISO Open Systems Interconnection (OSI) model

transmission, reception and decoding, as well as timing and synchronization. It is the only portion of the physical layer being defined by the CAN specification, and any driver/receiver and transport medium could be used in a CAN system as long as these devices meet the PS requirements. PMA, which describes driver/receiver characteristics, and MDI, which described connectors/wires, are not defined by CAN specifications.

While ISO standard does not specify the physical wires and connectors to be connected to the line, it does require that the wires and connectors meet the electrical specification of having 120 Ω (nominal) terminating resistors at each end of the bus. Figure 3.6 shows a principle schematic of CAN nodes (i.e., electronic control units, noted as ECUs) to a CAN cable, via a CAN transceiver, to transmit signals. For achieving the most reliable and least error signal transmission, CAN protocol uses a differential voltage to represent the signal which requests CAN cable having two wires, referred to as CANH (CAN High) and CANL (CAN Low), to carry the signal. ISO 11898 defines two logical states, recessive and dominant, to represent a signal. Based on this definition, when the bus is waiting for receiving a signal, it is operating at a "recessive" state, represented as logic "1," and the voltage on both CANH and CANL is maintained at a reference value. When the signal is delivered to the bus system, it changes the operation state to a "dominant," represented as logic "0," which will raise the voltage on CANH and lower the voltage on CANL, both to their present levels to form a robust voltage difference between two wires. This signal transmission method is called "differential transmission."

Using a pair of signal wires, a multi-segment CAN system can link more than 100 ECUs with up to 30 nodes on any one segment. CAN system can either

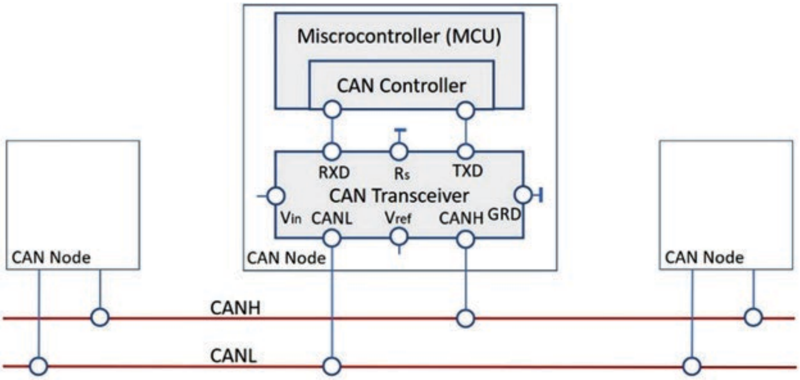

Fig. 3.6 Connection schematic of CAN nodes to a CAN cable

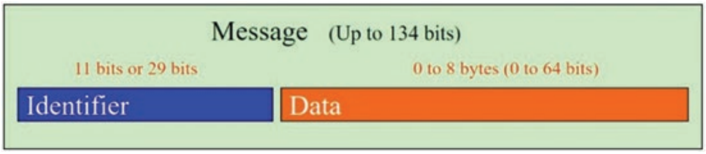

Fig. 3.7 Massage frame of CAN 2.0B

broadcast messages or data to all nodes in the network or exchange only between identified communication partners. To securely communicate with right partners using physically the same cable, the CAN protocol uses a well-defined message frame and uniquely assigned address code for each node. ISO 11898 defines a two-segment message frame for "identifier" and "data" as depicted in Fig. 3.7. The identifier segment may carry 11 bits (Standard CAN) or 29 bits (Extended CAN). ISO standard uses the first bit (identifier extension or IDE) to identify if a particular identifier is 11 or 29 bits. If IDE is 0, then it is an 11-bit identifier; if IDE is 1, then it is a 29-bit identifier. The identifier can be used for any purpose; often, it is used to identify the type of message, the communication partner of the message, and the message priority. When two nodes attempt to send messages at the same time, the message that has a higher priority (represented by dominant bits) will go first, and the one with a lower priority (represented by recessive bits) will wait until the next time the bus idles to retry sending. This function permits all nodes to access the bus based on their priority. While an individual node receives a broadcasted message, it will also decide whether or not to receive and process the message based on the message carried in the identifier. Functioning like a data highway by allowing multiple nodes to share the same set of wires for data transferring, a CAN bus can transmit message quickly (up to 1 Mbps) and reliably (error rate of less than one in 21 billion messages) and is well suited for high-rate short message communication. Such features provide the CAN bus the capability of supporting distributed real-time control with a very high level of security.

3.2.1.4 Optical Fiber Data Transmission Technology

The adoption of light as a communication medium dates back to the early experiment of the American scientist Alexander Graham Bell and his assistant Charles Sumner Tainter in 1880. In their experiment, Bell modulated sound signal into beam and successfully transmitted sound signal to a distance about 213 m apart which laid the base for utilizing light beam as a carrier for communication. Because Bell took the atmosphere as the transmission medium of optical signal in his exploring experiment, the signal inevitably faced various unstable interferences and high attenuation rate in transmission. The problem was tough to cope with, and it was not until laser and optical fiber technologies matured that optical communication technology became practically usable. In 1965, Charles Kuen Kao, a Chinese American scientist, proposed that the attenuation rate of optical signal used in optical fiber communication could be reduced to 20 dB·km^{-1} in comparison to 1000 dB·km^{-1} using glass fiber commonly used at that time (Huang and Li 2010). In the next year, Kao's team discovered that high-purity silica was the ideal medium for optical fiber communication, and they found that the high attenuation rate mainly came from a large number of impurities in the glass fiber, rather than "scattering is the main reason for the high attenuation rate" that many physicists thought at that time. In the next few years, Kao's efforts drew the attention of Bell Laboratories which successfully promoted optical fiber communication. In 1970, Corning, a US-based firm, invented and manufactured the first optical fiber that could achieve the attenuation rate of optical signal to 20 dB·km^{-1} and be practically used in commercial communication. At the same time, as GaAs semiconductor laser technology matured, ideal light source was brought to optical fiber communication technology, which jointly promoted the practical application of optical fiber in long-distance communication.

The first generation of commercial optical fiber communication system was built in 1975 which used GaAs semiconductor laser source to form optical signals with a wavelength of 0.8 μm that propagate in the optical fiber. This system achieved a transmission rate of 45 Mb·s^{-1} and extended the relay distance to 10 km. In 1977, General Telephone and Electronics (GTE) commercialized its optical fiber communication lines and laid the first fiber-based telephone communication line in Long Beach, California, USA. This line achieved a transmission rate of 6 Mb·s^{-1}. Later in the same year, the second optical fiber communication line of 9 km long was completed in Turin, Italy. The Italy line used a two-wire laying mode which increased the transmission rate to 140 Mb·s^{-1}.

Optical fiber communication technologies were continuously improved after that. The second-generation technology was developed in the early 1980s which characterized using 1.3 μm optical signal for reaching high transmission speed (up to 1.7 Gb·s^{-1}) and long relay distance (reached 50 km). Based on this newer technology, big communication networks could be built. For example, SaskTel, a Canadian service provider, built the world's longest commercial optical fiber network at that time, with a total of line length of 3268 kilometers to connect 52 communities. The discovery of indium gallium arsenic compounds and the development of indium gallium arsenide photodiodes helped to upgrade the technology to its third generation which used 1.55 μm optical wave to help reduce attenuation to 0.2 dB·km^{-1} and achieve a transmission rate of 2.5 Gb·s^{-1} with a 100 km relay distance. The fourth-generation technology was based on wavelength-division multiplexing (WDM) and optical amplification technologies. The WDM technology could transmit multiple optical carrier signals onto a single optical fiber by using different wavelengths of laser light which exponentially increases the capacity of signal transmission in optical fiber. For instance, a 128 wavelength WDM technology could increase transmission capacity 128 times over than that of single wavelength transmission. Similarly, the optical amplification technology significantly improved the relay distance which helped to reduce the laying and maintenance costs. Since deploying the fourth-generation technology, the communication speed increased dramatically and reached 10 Tb·s^{-1}.

Optical fiber communication technology has now upgraded to its fifth generation which adopts low water peak optical fiber to achieve predictable wavelength range expansion. There are only three low loss wavelength windows, 850 nm, 1310 nm, and 1550 nm, in traditional optical fiber. In recent years, the L-band window, the fifth window (all wave fiber), and the S-band window have been developed one after another. The significance of these inventions lies in the creation of a low loss wavelength window with a width of 1280~1625 nm, which achieves a substantial increase in transmission capacity. In addition, the application of optical soliton, i.e., ultrashort optical pulse signal, features inherent advantages in relation to dispersion cancellation and transmission capacity. It is worth mentioning that such application is also the future trend of optical fiber communication (Li and Zhang 2017).

Multiplexing in Optical Fiber

Multiplexing in optical fiber is a way of transmitting multiple signals over a single optical fiber line. There are mainly three techniques used in fiber-optic multiplexing communication today: wavelength-division multiplexing (WDM), frequency-division multiplexing (FDM), and time-division multiplexing (TDM). Studies on developing novel multi-core multiplexing (MCM) are increasingly reported in the past decade.

Wavelength-division multiplexing (WDM) could be today's most useful means in high-capacity communication. WDM uses a technique of modulating to multiple signal streams of different wavelengths in terms of colors of laser light onto a single optical fiber. At the transmitting end, a multiplexer (MUX) is used to combine the signals into a light signal band, and at the receiving end, a de-multiplexer (DEMUX) is needed to divide transmitted signals separately. WDM is done in the IR portion of the electromagnetic spectrum. Currently, the commonly used wavelengths for optical fiber communication are 1310 and 1550 nm, as low signal attenuation would occur if a bandwidth of 100 nm or less light signal was transmitted in an optical fiber which makes it possible to create two communication windows, i.e., bands of 1250–1350 and 1550–1600 nm, to increase the total signal carrier bandwidth to 200 nm. If the optical carrier were divided by a 1 nm spacing, then more than 200 channels could be used for communication. As today's technology could divide light waves in a 0.4 nm spacing, it could significantly increase signal transmitting capacity in optical fibers, thereby laying the foundation for the application of WDM technology (Rohde et al. 2014). Today's mainstream WDM products could host 80 channels of bi-directional communication.

The optical frequency-division multiplexing (FDM) is a technology that works as a technique of multiplexing to combine multiple signals of different frequencies to be transmitted over a shared medium concurrently. In FDM, the total bandwidth is divided to a set of frequency bands that do not overlap. Each of these bands is a carrier of a different signal that is generated and modulated by one of the sending devices. The frequency bands are separated from one another by strips of unused frequencies called the guard bands, to prevent overlapping of signals. Similar to WDM, FDM also requires having a MUX to combine modulated signals at the sending end to transmit multiple independent data streams simultaneously and a DEMUX at the receiving end to extract individual signals from the combined signal. At present, because there are still some technical challenges, FDM technologies are mainly used in local network and user access network in integrated optical fiber communications (Yao 2013).

Optical time-division multiplexing (TDM) technology refers to a new technology for shared transmission of low-frequency and low-speed pulse-frequency optical signals on one optical fiber channel at different time slots in a format of high-speed, multiplexed pulse signals. In principle, such pulse signals are transmitted in a frame structure. The time domain of an optical signal can be divided into multiple equal-length gaps, and the modulated single pulses transmitted by the signal transmitting equipment in each channel occupy a certain gap. The hardware components needed for time-division multiplexing are similar to wavelength and frequency counterparts, of course with their own specific working principles (Faruque 2015). When TDM technology is applied in a communication network, the average broadband allocated by each network node could be decreased which makes this technology more suitable for being used in LAN.

Multi-core multiplexing (MCM) technology is an intuitive way to improve the capacity of a single fiber. Compared with the approach of putting multiple SMFS (single-mode fibers) in the same casing, multi-core fiber (MCF) effectively improves the spatial density of optical fiber. The key technologies of MCM system include MCF design, fan in and fan out multiplexing, multi-core fiber amplification, multi-core alignment fusion, and transceiver integration. The performance parameters and characteristics of MCF, such as effective area, loss, and dispersion, resemble that of SMF, allowing the system to support Pbit/s transmission capacity in single fiber and provide switching dimension based on spatial multiplexing (Lai et al. 2017).

Optical Fiber Access Technology

Optical fiber access technology is a broadband network access technology that transmits high-speed data, high-fidelity music, and video to millions of households. Optical access network can be divided into active optical network and passive optical network. Active optical network refers to ATM (Asynchronous Transfer Mode), SDH (Synchronous Digital Hierarchy), Ethernet, and other technologies, while passive optical network refers to systems without any active components. According to the different arrival positions of optical fiber, the optical fiber access network can be further divided into four types: Fiber To The Cab (FTTCab), Fiber To The Curb (FTTC), Fiber To The Building (FTTB), and Fiber To The Home (FTTH) (Liang 2013).

Optical Switching Technology

In traditional fiber-optic communication, to cope with the loss and dispersion of long-distance transmission fibers, electronic repeaters are used for optical-electric conversion, electrical amplification, and electric-optical conversion at relay stations located at specific distances. Yet it is precisely because these electronic circuits are added to the optical fiber communication system that the full advantages of optical fiber communication are significantly restricted. Developed to address this problem, the optical switching technology refers to the direct exchange of optical signal, freeing the signal from having to go through the optical-electrical-optical conversion. Moreover, the technology gives full play to the high-speed, broadband, parallel processing of optical signal in the process of exchange, with strong anti-interference ability and other outstanding advantages. In the past a couple of decades, a few new structures and/or technologies of optical switching have been formatted or created, such as cursor mark switching integrated with IP technology, optical burst switching combining circuit switching and packet switching, photon IP routing implemented in the optical domain, soft switching based on distributed network management, multi-grain optical switching based on GMPLS, and intelligent optical switching (Ma and Kuo 2003).

All-Optical Networking Technology

Today, many Internet-based networks have been upgraded to all-optical networks, i.e., all data transmission and exchange processes between the main station and all end-user nodes are being connected using fiber-optic cables. One of the most important advantages for such an upgrade is it helps to eliminate electrical signal intervention in data communication.

Building an all-optical network requires applying some special key technologies (Jin 2015). The first could be the switching technologies, such as optical path switching and packet switching, needed for controlling data transmission in light media. Optical cross-connect (OXC) manages optical signals' cross-connection and therefore is essential for managing optical transmission effectively and ensuring the system is working reliably.

Other core technologies in all-optical networks are aforementioned optical multiplexing, such as the optical add-drop multiplexer (OADM) technology for multiplexing and routing different channels of light into or out of a single-mode fiber (SMF) and the wavelength-division multiplexing (WDM) technology for combining and transmitting multiple signals simultaneously at different wavelengths on the same fiber which could increase bandwidth over existing fiber networks. WDM products can be divided into three wavelength patterns of normal (WDM, using two normal wavelengths of 1310 and 1550 nm on one fiber), coarse (CWDM, providing up to 16 channels using multiple transmission windows), and dense (DWDM, using 1530–1565 nm transmission window to provide 40 channels at 100 Ghz spacing or

80 channels at 50 GHz spacing). It is worthy to point out that there are new multiplexing technologies available for providing better performance products.

Applications of Optical Fiber Networks

Due to aforementioned advantages of optical fiber in communication, this technology has been adopted very quickly in communication, especially those requiring huge data, high speed, and long-distance applications, over the past a couple of decades. Telecommunication transmission could represent the primary application of optical fiber networking technology. Fiber-optic networks have become, in most developed countries, and are becoming, in many developing countries, the trunks of communication networks.

Optical fiber communication networks can be divided into three levels of wide area network (WAN) which covers a huge area such as a region, a country, a continent, to worldwide and may be shared by multiple telecommunication providers to construct, manage, and maintain; metropolitan area network (MAN) which covers a large area such as a town, a city, to a region to meet the communication needs among different users within the coverage area and most times is part of WAN; and local area network (LAN) which covers the smallest area such as a home, a farm, a company, and so on and can be owned and operated by private owners.

Today, optical fiber communication has been adopted by almost all industries, for the common advantages or industry-specific benefits. A few examples include the applications in power system specially for its outstanding performance on anti-interference in intensive noisy environment of electrical noises; in high-speed rail systems for reliable and error-free long-distance real-time signal transmission for maximizing the safety; and in some hazardous environments such as chemical plants, oil depots, and coal mines utilizing its anti-corrosion, anti-radiation, fire resistance, and anti-explosion features for safe operations.

3.2.1.5 Powerline Carrier Communication Technology

Powerline carrier (PLC) is a communication mode of using the existing public and private wiring for the transmission of analog or digital signals which could remove the need for separate investment for data communication (Huo 2016). The history of this technology can go back to the 1920s, and powerline carrier communication on high-voltage power lines has been used widely since. Nowadays, the communication networks of different types have covered most of the areas in many countries; still, the high-voltage powerline carrier communication remains one of the major means of communication in many places and applications. In comparison, communication using low-voltage powerline has more technical challenges, such as the high signal attenuation, high noise, and high deformation. However, as it is closer to the user and easier to access, low-voltage PLC has inestimable market prospects (Wang 2004).

Principle of Powerline Carrier Communication

Powerline carrier communication normally applies orthogonal frequency-division multiplexing (OFDM), also known as discrete multi-tone (DMT) modulation, for signal modulation. OFDM works to divide the channel into several orthogonal sub-channels, then convert the high-speed data signal into parallel low-speed data stream, and finally modulate it to each sub-channel for transmission. Although the signal transmission rate of each subcarrier is not high, a high transmission rate can be obtained by combining all sub-channels. As a mature technology that is resistant to inter-symbol interference (ISI) and inter-channel interference (ICI), OFDM boasts unique advantages. First, OFDM maximizes the use of spectrum resources. Traditional frequency-division multiplexing reserves guard bands between sub-channels, while in OFDM, there is orthogonality between the subcarriers of the OFDM system, allowing sub-spectrums to overlap each other. Second, different transmission rates in the uplink and downlink can be achieved using different numbers of sub-channels, which can be easily combined with other access methods to form an OFDMA system. Third, since the abovementioned interference affects only a small part of the subcarriers of one OFDM system, the OFDM system is not threatened by narrowband interference. Based on the same principle, OFDM also features resistance to frequency selective fading and multipath effects.

At the same time, due to the existence of multiple orthogonal subcarriers in the OFDM system, and because the output signal is a superposition of multiple sub-channels, the system is also exposed to several shortcomings. First, low sensitivity to frequency deviation is the primary disadvantage of OFDM system, because once there is frequency deviation between the local oscillation frequencies of transmitter and receiver, the orthogonality between the sub-channels of OFDM system will be destroyed, resulting in interference between the sub-channels. Second, when multiple signals are in the same phase, the instantaneous power of the superimposed signal will be much higher than the average power of the signal, resulting in a high peak-to-average power ratio. Third, if the linearity of the amplifier in the transmitter cannot meet the requirements, it may lead to signal distortion, which may, in turn, cause the change of signal spectrum and the destruction of the orthogonality between sub-channels, worsening system performance at last (She et al. 2012).

PLC Networking Methods

There are multiple analytical methods that can be used to find optimal logical topology for PLC networks, such as simulated annealing (Liao and Tao 2006), genetic algorithm (Xu et al. 2007), tabu search (Mehenni 2018), ant colony algorithm (Tirkolaee et al. 2019), and particle swarm optimization (Chatterjee et al. 2017). Research on these bionic algorithms has been evolving through theory and application, but at the same time, defects still exist. Therefore, the networking of PLC is still a research focus. Extensive researches have been conducted for finding effective and accurate ways for optimizing PLC network when the structure of the PLC network and the location of each communication node are unknown. At present, the low-voltage power line carrier communication is mainly used in the fields of carrier meter reading, street lamp control, and so on, but these fields are often accompanied with rough environment, complex network, and limited development prospect (Yang 2013). PLC can be classified into high-, medium-, and low-voltage powerline carrier communications. To elaborate the networking mode of PLC in rural area for agriculture applications, this book focuses on the networking algorithm of low-voltage power carrier.

The networking of a low-voltage PLC network is to determine an optimal logical topology using certain analytical algorithms, with one fundamental task to find out so-called solitary points, some subcarrier nodes that cannot establish a signal communication with the main carrier node no matter what kind of relay methods is being used. This type of node should be excluded from the PLC logical topology. A three-step analytical approach is often used in searching for such an optimal logical topology for low-voltage PLC network (Liu et al. 2009). This method can be briefly described without going into the technical details as follows:

Step 1: The main carrier node in turn sends test packets to poll all subcarrier nodes, and subcarrier nodes send a reply to main carrier nodes after receiving test packets. It can identify n subcarrier nodes out of a total of m nodes capable of communicating with the main carrier node, and these n nodes are classified as the first-layer subcarrier nodes. If $n = m$, it means that all subcarrier nodes can directly communicate with the main carrier node and no polling process and relay are needed. If $n < m$, then continue to go to step 2.

Step 2: Sequentially pull testing message from subcarrier node 1 to n being identified as the first-layer nodes to those not being identified, namely, the remaining (m-n) nodes. For those nodes that could not establish a direct communication with the main carrier node, but can respond to one of the first-layer subcarrier nodes, i, to form an indirect communication with the main carrier node, then those subcarrier nodes can be identified as the sub-nodes of the first-layer node i, and we can define those as the second-layer subcarrier nodes to distinguish from those that could directly communicate with the main node. If no second-layer node could be identified, then it implies that all those m-n non-first-layer nodes are all “solitary points” and then a logical topology diagram could be created to exclude those points in the PLC network. If there were at least one node being identified as the second-layer node, then those nodes need to be aligned as the sub-nodes of identified first-layer node, including those in the network logical topology.

Step 3: Repeat step 2 as needed to see if a third layer of sub-node could be found.

Applicability of PLC in Network Communication

With recent development, PLC has been widely adopted in transportation system, industry production, and daily life, such as transportation signaling and monitoring on railway, subway, and highway, street and traffic light controls, power grid monitoring and remote metering, plant (such as warehouse and greenhouse) monitoring and controlling, and medical monitoring systems (Gao et al. 2009). In addition, PLC has great prospects for information engineering in remote equipment control, voice communication, and video monitoring for some places where conventional communication networking technologies are difficult to apply, such as underground mining sites and remote farms.

Smart home refers to the use of a set of networked electronic systems or appliances remotely programmable, monitorable and controllable for achieving improved comfortability, safety and security, living experiences and conveniences of people via sensing, control and communication technologies. Since there already exists a household powerline which makes it convenient to use PLC communication technology for household networking, the automatic control of household appliance could help to achieve a higher power efficiency to have high-quality life with less energy consumption at the same time (Xu 2013). According to the standards of the HomePlug Powerline Alliance (HPA), an organization committed to the formulation of communication technology standards for home power line network, the powerline-based home LAN can be built simply by inserting the power head into the pre-installed socket. The transmission rate of this LAN can reach 14 $Mb \cdot s^{-1}$, and there remains great potential for future development.

In terms of communication rate and carrier frequency, PLC technology can be divided into three categories of (1) low-rate (less than 1 kbp), mainly for long distances (>1 km) and often utilizing 25 KV high-voltage grid as the carrier; (2) medium-rate (1~50 kbps), mainly for digital communication between fixed points in general using a carrier frequency between 50 and 350 kHz; and (3) high-rate (above 100 kbps), mainly for high-traffic data communication within small areas suitable for computer networks and often using a high carrier frequency of 1.7 to 30 MHz (Li 2002).

With the continuing development of communication networking technology over the past a few decades, requiring more and more high-rate and high-capacity communication, the use of PLC technology in medium- and high-voltage power network is gradually diminishing, but due to its convenient installation conditions, the application and development of this technology in the low-voltage distribution network is just emerging. With the development of information technology and the popularization of smart grids, diversified communication technologies have witness significant improvements, and carrier technology, as a low-cost communication method with great development potential, will certainly play a more important role in the future.

3.2.2 *Wireless Communication Technology*

As agricultural production is mostly occurring in farming field, distance away from where wired communication could support, therefore wireless communication becomes unavoidable for agricultural IoT systems and applications. Similar to its wired counterpart, wireless communication can be grouped into point-to-point and point-to-multipoint communications (Zhang and Ehsani 2006). Implied by their names, point-to-point communication is when only one device transmits signals and only one other device receives those signals, such as computer to printer and controller to sensor. A few different communication technologies, such as radio frequencies, IrDA, and Bluetooth, can be used for point-to-point communication. In comparison, point-to-multipoint communication is when one device transmits a signal and multiple devices receive that signal, similar to broadcast television where the signal is sent and received by many TV viewers. The “receivers,” that is, the television sets in this case, do not communicate with each other. Methods of point-to-multipoint communication include wireless LANs and cellphone networks.

3.2.2.1 Radio-Frequency Communication Technology

Implied by its name, radio-frequency (RF) communication technology uses radio waves, electromagnetic bands from 3 kHz to 300 GHz, as media to send and receive message wirelessly. RF wireless communication systems have been around for many years with a broad range of applications from garage door opener to satellite communication. Physically, RF devices use an antenna and a radio transmitter in the device to send and receive signals or a transceiver which can do both. A few RF devices we can see in our everyday life include cellphones, citizen band (CB) radios, broadcasting TVs, automobile navigators, wireless keyboards, and wireless mice. A few specifically branded wireless technologies, such as Bluetooth, Zigbee, Wi-Fi, and GPS, are all communicating in the RF range. In agriculture, RF technology is commonly used in wireless meteorological stations, RFID readers for livestock identification, and some field-deployed wireless sensors emitting signals in than range of 20 to 900 MHz.

One RF technology finding a broad application in agricultural IoT system is radio-frequency identification (RFID) technology. RFID system is a short-range wireless communication technology that uses a RF reader to detect and read encoded digital data in electronic tags or smart labels for some newer systems. Illustrated in Fig. 3.8, a basic RFID system consists of three elements of an electronic tag (or a smart label, all called the “tag” hereafter), an RF reader, and an antenna, supported by associated electronics (labeled as a high-level system in the figure). In use, electronic tags are attached to objects to be identified and tracked. When the objects of interest enter the detectable range of the RF reader, it will read the information kept in the tags and transmit the information via the Internet so people can get the needed information of the object of interest (Song 2006).

Electronic tag: An RFID tag is made of an integrated circuit and an antenna, packaged within some protective materials in various shapes and sizes suitable for different applications under different environmental conditions. RFID tags can be packaged as active and passive ones, with the former carrying its own power supply (often battery) and the latter being “powered up” by the RF reader before transmitting the data. Passive tags are more widely applied in agriculture, as they are smaller and less expensive to implement. Active tags often carry onboard electronics, such as sensors, microprocessors, or even input/output ports, to allow the tags to be used in a wider range of applications. Different from electronic tags, smart labels incorporate both RFID and barcode technologies by inserting an electronic in an

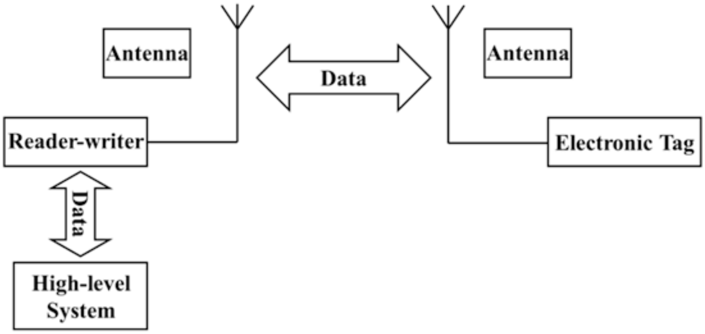

Fig. 3.8 Basic composition of RFID system

adhesive label to add a feature of barcode and/or other printed information for being detectable by other identification and tracking systems, such as vision. However, it could make programming RFID tags more complicated and requires more advanced equipment.

RF reader: In an RFID system, RF reader (also called reader-writer or interrogator) is the device that transmits and receives radio waves to communicate with RFID tags. In operation, the reader first transmits a specific radio wave signal; when the electronic tag receives this signal, it will give a feedback signal that contains the encoded information in the tag. After the reader receives the feedback signal, it will transmit the signal to the processor for appropriate operations. RF readers can be fixed at specific locations for detecting and identifying objects of interest passing by or on mobile platforms to search for objects of interest.

High-level system: There might be multiple RF readers in a complex RFID system. Each reader may interact with multiple electronic tags at the same time and process data information in real time, which demands having a high-level system for processing the acquired information. The high-level system is often a computer network system, including the data exchange and management functions. It can also connect RF readers to the Internet to make it a node in an IoT system.

3.2.2.2 Frequency Modulation Communication Technology

Despite amplitude modulation (AM) being in used in many RF communication applications, the interest on using frequency modulation (FM) communication technology is getting more mainly due to its capability on higher fidelity in carrying original signal during communication process to more accurately and completely represent the original signal. Different from AM technology which modulates the amplitude of carrier wave to encode signals to be transmitted, FM encodes the signal by modulating the carrier wave frequency which is less sensitive to electronic environment and therefore will be less interfered by other electromagnetic signals; today, there is too much, to achieve high-quality communication. However, FM does have a higher requirement on its communication equipment and has a short communicable distance.

FM signals can be classified into two classes of “narrowband” and “wideband” in terms of the bandwidth of the radio channel being used. In general, the bandwidth of wideband FM (WBFM) wave can be 15 times broader than that of narrowband FM (NBFM) wave. The benefit of using NBFM is the lower noise bandwidth and hence better sensitivity and range, and that of WBFM is the capability to transfer higher data rates. Therefore, WBFM is more commonly used in high-quality signal transmission, such as music transmission on FM radios, and NBFM is more suitable for mobile communications.

In principle, there are two methods of frequency modulation: direct frequency modulation and indirect frequency modulation. Direct frequency modulation uses a voltage-controlled oscillator (VCO) to generate a wideband FM (WBFM) wave whose instantaneous frequency (f_i) is proportional to the input signal voltage ($f_i \propto v(t)$) which is similar to the definition of FM wave. A phase-locked loop (PLL), a closed-loop automatic control system (as shown in Fig. 3.9), is normally used in this process to track the phase of input signal. This technology has been extensively adopted in various fields of radio technology as high-stability frequency source. When PLL works in the frequency modulation state, its phase discrimination remains unchanged; hence, PLL remains in the locked state. Moreover, the low amplitude of modulation signal is unable to disrupt the locked state of PLL; thus, the frequency stabilization of PLL remains. However, since the phase detector and the loop filter have certain hysteresis characteristics, the output control voltage of the loop filter cannot keep up with the change of the modulation signal, which is why the output frequency of the VCO is directly controlled by the modulation signal in a certain range, thus realizing frequency modulation.

Indirect frequency modulation generates a WBFM wave indirectly by first generating a NBFM wave and then using a frequency multiplier to get WBFM wave.

3.2.2.3 Wi-Fi Communication Technology

Wireless fidelity (Wi-Fi) is a family of wireless networking technologies used for local area networking (LAN) and Internet accessing being specified by IEEE 802.11 family of standards. A few most significant advantages are its high transmission speed, up to 11 Mb·s^{-1}, its long effective distance, and its easy applicability to a large number of IEEE 802.11 DSSS (direct-sequence spread-spectrum) compatible equipment.

Featuring a maximum bandwidth of Mb·s^{-1}, the IEEE 802.1lb wireless network specification was developed based on the IEEE 802.1la network specification. In the event of weak signals or interference, the bandwidth could be adjusted to 5.5, 2.0, and 1.0 Mb·s^{-1}. This automatic adjustment of the bandwidth effectively ensures the stability and reliability of the network. In open areas, the communication distance can reach 305 m, while in the closed area, the communication distance is 76~122 m. This wireless network can easily integrate with the existing wired Ethernet network

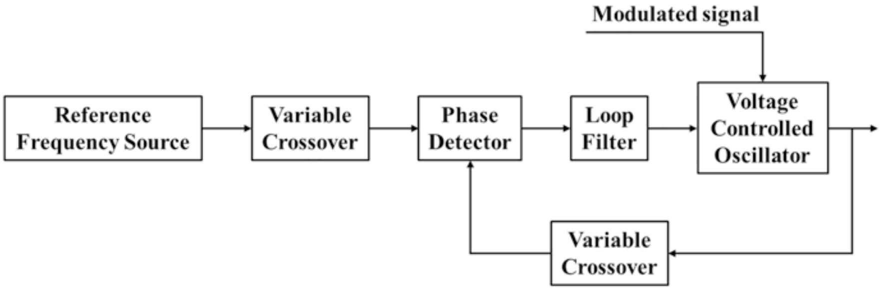

Fig. 3.9 A system block diagram of direct frequency modulation supported using a phase-locked loop (PLL) system

at low costs. Wi-Fi technology has now been widely recognized, and as long as there is Wi-Fi wireless network coverage, people can connect to the Internet at any time to acquire any information they need.

The major features of Wi-Fi technology include:

- There is wide wireless network coverage, and no wiring is required. Boasting a radius of up to 100 m, Wi-Fi is not restricted by wiring conditions, making it highly suitable for mobile working. At present, it has expanded from such industries as medical care, inventory control, and management services to include more industries and more people's daily life.
- Health and safe. The range of transmission power specified by IEEE 802.11b is below 100 mW; the actual transmission power falls within the range of approximately 60–70 mW. Furthermore, wireless networks, unlike some other electronic devices, do not directly engage with the human body which makes it safe to use.
- Fast transmission speed. Able to reach 11 $Mb{\cdot}s^{-1}$, Wi-Fi meets most communication needs for between individual devices and among a group of devices. However, as one kind of IP-based wireless networks, it shares the common shortcomings of low bandwidth, small coverage radius, long switching time, and a few more.

As for the application in Smart Home, relying on the Wi-Fi-supported system (normally consisting of a Wi-Fi socket, a wireless router, a remote server, mobile phone control terminal, and Internet access), home appliances, such as air conditioners, water heaters, and coffee machines, can all be remotely controlled, and people can make appropriate arrangements on their way back home. In general, a Wi-Fi smart home system is relatively inexpensive, simple to install, convenient to use, easy to control, and accessible remotely by smartphone and has zero disruption to the existing decoration.

The working principle of the Wi-Fi socket can be thus defined as follows. First, the Wi-Fi socket configures the name (SSID) and key of the router to which the module is connected through the configuration program on the mobile phone. It then configures the IP address of remote server to be connected. Third, the Wi-Fi socket power connects to the remote server via the configuration module. Fourth, control terminals such as mobile phones connect to remote servers to issue commands. Fifth, remote server sends user instructions to the Wi-Fi socket in the house. Finally, the Wi-Fi socket completes the corresponding on and off actions.

3.2.2.4 Bluetooth Communication Technology

As one of the commonly used RF communication methods, Bluetooth is a standardized protocol for short-range wireless connection technology. It supports radio communication for short-range (generally within 10 m) low-power wireless information exchange between many types of electronic devices via a 2.4 GHz wireless link. Bluetooth technology effectively simplifies the communication between mobile devices and between mobile device and the Internet. As a result, data transmission becomes more effective and seamless which broadens the scope for wireless communication.

A Bluetooth system forms a piconet, a wireless ad hoc network composed of individual devices communicating with each other directly, to support peer-to-peer communication. A piconet normally consists of one master device to interconnect with up to seven active slave devices, distinguished by a 3-bit MAC (medium access control) address, all being synchronized to a common clock and hopping sequence by the master device, in one physical channel. Up to 255 further slave devices can be inactive (or parked, namely, idling under a synchronized clock in the piconet but without a MAC address) which the master device can bring into active status at any time when an active link becomes available (Chen et al. 2015).

Bluetooth technology is ideal for forming an ad hoc network for wireless communication between fixed and mobile devices short-range. In agricultural IoT applications, Bluetooth technology can be used to construct worksite information monitoring systems using an ad hoc network (as shown in Fig. 3.10) to link sensors, displays, and data processing unit wireless to support real-time monitoring of farming operations.

3.2.2.5 Zigbee Communication Technology

Zigbee is another popular standardized protocol for RF wireless communication under the IEEE 802.15.4 physical radio specification and operates in unlicensed bands including 2.4 GHz, 900 MHz, and 868 MHz. A few very attractive application features of this protocol include (1) supporting multiple network topologies, such as point-to-point, point-to-multipoint, and mesh networks; (2) capable of having up to 65,000 nodes per network; (3) 128-bit AES (Advanced Encryption Standard) encryption for secure data connections; (4) DSSS compatible; and (5) low duty cycle and low latency. Such features make it suitable for many applications, such as industrial controls, wireless sensor networks, medical devices, smoke and intruder alarms, and home automation. As this technology has been widely used

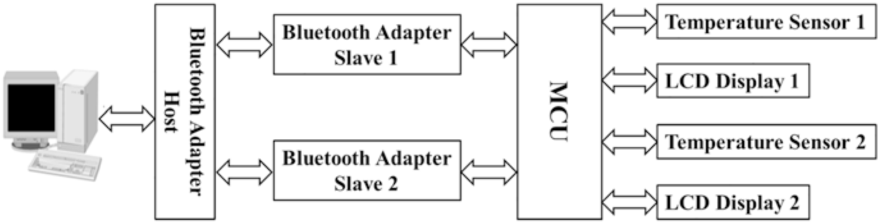

Fig. 3.10 System architecture illustration of a Bluetooth formed ad hoc network for farmland real-time monitoring

in agricultural IoT systems, a separate section later in this chapter (3.3.2) will provide more explanation on its applications in agriculture.

3.2.3 *Mobile Communication Technology*

Today, wireless communication achieved through mobile devices often refers to mobile communication and can be used in both point-to-point and point-to-multipoint communications, becoming more and more popular. The mobile communication technology is somewhat different from most of the wireless communication technologies introduced in the previous sections, and therefore it is worthy to have a separate section to introduce this technology.

3.2.3.1 Development of Mobile Communication

Since the first commercial mobile phone (based on the first generation of mobile technology) was introduced by Motorola in 1983, mobile communication technology has advanced very rapidly, with the fifth-generation technology being commercialized in 2019. The first generation (1G) mainly relies on analog technology and frequency-division multiple access (FDMA) technology. Due to the limitation of transmission bandwidth, the long-distance warm travel is not possible with 1G, which can only serve as a regional mobile communication system. 1G mobile communication suffer from a number of deficiencies, including limited capacity, low compatibility, poor security, low call quality, and failure to provide data services and automatic temperature tours.

Overcoming the weaknesses of analog mobile communication technology, the second-generation (2G) mobile technology successfully adopted digital time-division multiple access (TDMA) technology and code-division multiple access (CDMA) technology. Since the main purpose for 2G communication was voice transmission, 2G technology could satisfactorily provide digital voice services and low-speed text services. It brought major improvements of voice quality and privacy performance, as well as made it possible to perform automatic roaming within and outside a region. Another major advancement of 2G over 1G was it upgraded mobile technology from analog to digital. However, because 2G adopted different standards and the mobile communication standards were not unified, users can only roam within the coverage of the same standard. Therefore, global roaming was not yet possible. In addition, since the bandwidth of 2G digital mobile communication system was limited, data services were also restricted.

To address those issues, the third generation (3G) had a wider bandwidth, with a minimum transmission speed of 384 K, a maximum of 2 M, and a bandwidth of 5 MHz or more. 3G can be counted on to transmit voice as well as data, thus providing fast and convenient wireless applications, such as wireless access to the Internet. The ability to achieve high-speed data transmission and broadband multimedia services is another major feature of 3G mobile communications. The 3G mobile communication network can combine high-speed mobile access and Internet protocol-based services to improve radio-frequency utilization efficiency, hence providing global coverage that included satellites and enabling seamless connections between wired and wireless and services among different wireless networks. Besides, 3G also met the requirement of multimedia services, thereby providing users with more economical and more diversified wireless communication services. However, although the 3G mobile communication can be thousands of times faster than the transmission rate at the time, it was not able to meet the rapidly increasing needs for multimedia communication.

The invention of the fourth-generation (4G) mobile technology aimed at providing greater bandwidth capable of delivering high-speed data and high-resolution multimedia services with superior coverage, quality, and cost. According to the International Telecommunication Union's (ITU) definition, 4G is primarily a combination of 3G and WLAN that would be capable of transmitting high-quality video images, that would reach a transmission rate of 100 Mbps and an upload speed of 20 Mbps, and that would be able to meet all demands for wireless services. Furthermore, 4G realized seamless connection and compatibility with commercial wireless networks, local area networks, Bluetooth, and radio, television, and satellite communications while charging fees that would be the same as that of fixed broadband network. 4G would also feature higher data rates and spectrum utilization; enhanced security, intelligence, and flexibility; and improved transmission quality and quality of service (QoS). The 4G system was supposed to reflect the trend of continuous integration among mobile and wireless access networks and IP networks, which is why the 4G system should be an all-IP network.

The development of the fifth-generation (5G) mobile communication technology aimed to boost communication speed to have fast transmission rate, large-capacity access, and short network delay for meeting diversified needs (Li 2017). Specifically, it targeted to achieve a maximum downlink speed of 10 $GB \cdot s^{-1}$ (the data transfer speed between the mobile device and the wireless access point), equivalent to a download speed of 1.25 $GB \cdot s^{-1}$. 5G also need to support a wide range of application scenarios and boast broad prospects in the new information age. The technology relies on and opens technical design frameworks. As 5G undergoes technological changes worldwide, a few major accomplishes were achieved by different companies. On May 13, 2013, Samsung announced that it has successfully developed the core technology for 5G. On May 29, 2015, Coolpad made the first reference of a new 5G concept – terminal base station. On February 9, 2017, the International Telecommunications Standards Organization 3GPP announced the official logo of "5G." On December 1, 2018, three major telecommunication companies of Korea simultaneously launched 5G services in some parts of South Korea. On June 6, 2019, three major Chinese telecommunication companies successfully obtained commercialization licenses for the use of low- and mid-band 5G systems in China.

3.2.3.2 GPRS Communication Technology

General packet radio services (GPRS) is a wireless packet switching technology based on the global system for mobile communications (GSM). GPRS is often described as "2.5G" technology, meaning that this technology lies between the mobile communication technologies of 2G and 3G. It provides medium-speed data transfer using time-division multiple access (TDMA) channels that are available in the GSM network.

The primary characteristics of GPRS communication include its full use of the nationwide GSM network, large coverage, fast transmission rate (theoretical maximum rate 171 Kbps), short login time (the average connection time 2 s), real-time online service (keeping users online constantly), fees charged only by traffic volume, and the fact that data can be sent and received in packets (Liu 2008).

GPRS-based networks usually consist of four parts: GPRS network (data transmission channel), GPRS data transmission unit (GPRS DTU), multiple user data terminals (multiple terminal interfaces), and data center (receiving and processing data and returning processed data for display). The GPRS data wireless communication system enables transmitting data transparently between data collection terminal and data center. The terminal interfaces often include RS-232, RS-485, and/or TTL.

GPRS-based technology could be the first mobile communication technology being used in agricultural IoT system. One example was a farmland water-saving irrigation control system based on GPRS communication. This IoT-supported automated irrigation control system was composed of a remote monitoring master station and a few local substations (often the solenoid valves with an intelligent terminal). Its central control system receives signals transmitted from remote substations via the GPRS network, makes control decisions, and then sends out the control signals relevant to substations for automatic implementation. To have the needed accuracy and reliability in data transmission using this technology, the wireless data transmission distance should be limited at 1000 m or less.

3.2.3.3 4G Mobile Communication

The evolution of mobile communications from 2G to 3G transformed the core network from circuit switching to packet switching. 4G makes the core network independent of the access technology. Packet switching technologies include Asynchronous Transfer Mode (ATM) and Internet protocol (IP); the latter is considered the most suitable network layer technology for 4G mobile communications. A unified IP core network would bring together different wireless and wired access technologies. Figure 3.11 shows the network structure of 4G mobile communication. Within this structure, the core IP network serves as a unified network that supports wired and wireless access. It resembles a fixed network with mobile management capabilities, and its access points can be either wired or wireless. The wireless access point can be a base station of a cellular system, a WLAN, or an ad hoc network. An IP network could make managing connection through specific gateways easier. In addition, the demand for the speed and capacity of hotspot communication or the overlapping of network laying will make the entire network appear interconnected, integrated, and overlapped, resembling WAN and LAN (Choi et al. 2007).

In light of the huge challenges that have emerged alongside 4G, we can study the basic theories and key technologies in 4G by layers (as shown in Fig. 3.12). Let us now examine the main problems solved at the physical network layer. Since in 4G, high-speed data information needs to be transmitted under limited frequency resources, the system needs to adopt a high-spectrum efficiency modulation technology that can effectively resist multipath delay. Because 4G access technology uses orthogonal overlapping spectrum and features high spectral efficiency, it is recognized as the core technology of 4G at present. Due to the increase of the carrier

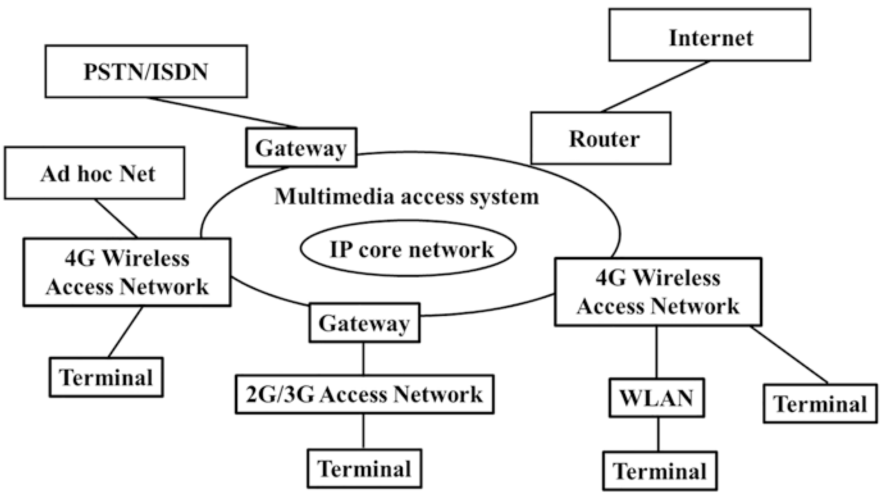

Fig. 3.11 Network structure of 4G mobile communication system

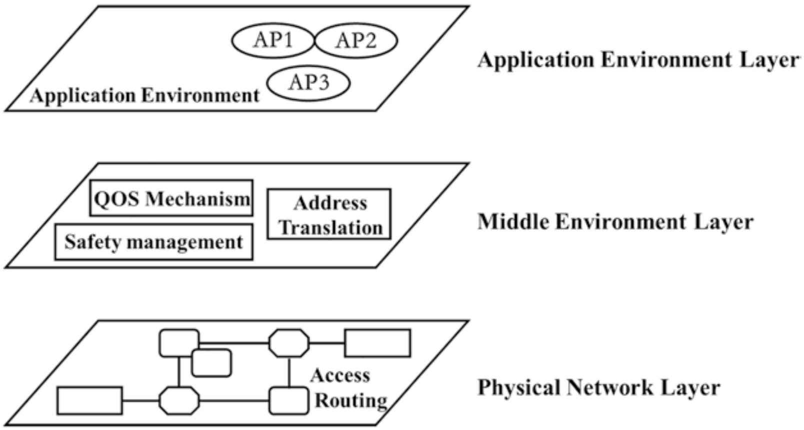

Fig. 3.12 A network layering diagram of 4G mobile communication system

frequency in 4G, the use of multiple antenna structures is not possible. Thus, adequate space-time signal processing technology becomes critical. There is unavoidable interference among multiple users in the communication environment, and because joint transmission (JT) and joint detection (JD) allow comprehensive consideration and utilization of the interference among multiple users, the system performance can be markedly improved.

The intermediate environment layer offers solutions to the following problems: when a variety of packet services with different requirements are converged to the wireless interface for shared transmission in 4G system, the quality of service (QoS) requirements such as delay and rate, a schedulable MAC layer mechanism is ensured by combining the characteristics of wireless link and the packet scheduling strategy. On this basis, resource allocation and packet transmission should be scheduled according to service attributes and link characteristics of wireless interface. In 4G, various real-time services and non-real-time services coexist and interact with each other, bringing more flexibility to wireless resource management. Therefore, it is necessary to consider an access control strategy under the coexistence of multiple services that adopts limited frequency resources and reasonable equipment configuration for improved system capacity or data throughput, hence ensuring user satisfaction.

The orthogonal frequency-division multiple access (OFDMA) 4G network used is sensitive to timing and frequency offset. Considering that 4G system is used in combination with other communication accessing technologies, such as FDMA (frequency-division multiple access), TDMA (time-division multiple access), and CDMA (code-division multiple access), time-domain and frequency-domain synchronization is especially important. Like other digital communication systems, synchronization is divided into two stages: acquisition and tracking. In the downlink, the base station broadcasts synchronization information to each mobile terminal, which is why the downlink synchronization is relatively simple and easy to achieve. In the uplink, signals from different mobile terminals must arrive at the base station synchronously to ensure the orthogonality between carriers. The base station extracts the information about time-domain and frequency-domain synchronization according to the subcarrier that carries the information sent by each mobile terminal, and it then sends the information back to the mobile terminal for synchronization, which can be carried out in time domain or frequency domain, respectively, or carried out simultaneously in time and frequency domain (Moose 1994).

Able to eliminate or reduce the interference between signal waveforms, OFDMA technology is not sensitive to multipath fading and Doppler frequency shift. It not only improves the spectral efficiency and is suitable for high-speed data transmission but also has strong anti-fading ability and anti-code interference ability. Channel coding and interleaving are often used to improve the performance of digital communication system. The former can be counted on to handle random errors in fading channels, while the latter can be relied upon to tackle burst errors in fading channels. In practice, channel coding and interleaving are usually used in combination to further improve system performance.

Software-defined radio (SDR) is an open structure technology which makes possible all kinds of radio communication systems using software loading method through a general hardware platform with standardized and modular hardware functional units. Its central idea lies in an effort to make the advanced modules, such as wideband A/D converter and D/A converter, reach the requirements of RF antenna and to define wireless functions with software. Its software system includes all kinds of wireless signaling rules and processing software, signal flow change software, modulation and demodulation algorithm software, channel error correction coding software, source coding software, etc. Software radio technology mainly involves digital signal processing hardware (DSPH), field-programmable device (FPGA), digital signal processing (DSP), and so on and so forth (Xiao et al. 1998).

Multi-user detection (MUD) technology used in 4G system can effectively eliminate inter-code interference. MUD is based on the idea that the signals of all users or some users occupying a channel ought to be treated as useful signals instead of interference signals and that the symbol, time, signal amplitude, phase, and other information of multiple users should be used to jointly detect the signal of a single user, i.e., comprehensively using various information and signal processing means to process the received signal so as to achieve the best joint detection of multiuser signal.

Multiple antennas are placed at both the base and mobile stations to form a multi-input and multi-output (MIMO) communication link between those stations. MIMO technology uses multipath to provide higher data throughput and to improve coverage and reliability without taking up extra radio frequency. It solves the two most difficult problems that any radio technology faces today, namely, speed and coverage. Its channel capacity increases linearly with the number of antennas. That is to say, the capacity of wireless channel can be multiplied using MIMO channel, and the spectrum utilization can be multiplied without increasing bandwidth and antenna transmission power. MIMO technology provides spatial multiplexing gain and spatial diversity gain for the system. Spatial multiplexing uses multiple antennas at the receiver and the transmitter to make full use of multipath components in spatial propagation. Using multiple sub-channels to transmit signals in the same frequency band makes the capacity increase linearly as the number of antennas increases. There are two kinds of spatial diversity: transmit diversity and receive diversity. As a research focus in this field, space-time code based on diversity technology and channel coding technology can obtain high coding gain and diversity gain. MIMO technology can provide high-spectrum efficiency and enhance the capacity and coverage of wireless system.

Smart antenna, an adaptive array antenna capable of auto-tracking multiple beams without switching, is considered one of the key technologies in 4G mobile communication. Smart antenna shaping beam can suppress the mutual interference in the space domain, enhance the desired signal in a special range, improve the signal quality, and increase the transmission capacity. Its basic principle is to use antenna array and coherent wireless transceiver at the wireless base station for the transmission of radio-frequency signals. At the same time, through the baseband digital signal processor, the signals received on each antenna link are combined according to a certain algorithm to achieve the uplink beamforming.

Since the 4G communication system adopts the full packet mode of IP to transmit data stream, IPv6 technology is used as the core protocol in a 4G network. This adoption is mainly based on the following two considerations: (1) the 128-bit IPv6 address could provide a huge address space (approximately 3.4×10^{38} addresses) which makes it possible to provide a unique address to all conceivable network devices in the world for a foreseeable future and (2) it supports stateless and stateful address auto-configuration to quickly obtain the right address.

3.2.3.4 5G Mobile Communication

As mobile communication technology is continuously advancing, 5G networking technology makes it practically possible to connect virtually everyone and everything together including machines, objects, and devices. To achieve those, it is also required that the 5G system can transmit huge amount of data more efficiently than 4G LTE (Long-Term Evolution) technology can provide which means a 5G system should have a stronger network reliability and a faster data communication speed and be able to connect more devices than a 4G system. Beyond those improvements, 5G technology is aiming to unleash a massive IoT ecosystem for all different applications, including agriculture.

Key Technologies of 5G

Different from the traditional concept of mobile communication system, apart from laying a focus on the point-to-point physical layer transmission, channel coding, and other classic technologies, 5G system is developed on a new concept of multi-point, multi-user, multi-antenna, and multi-cell collaborative architecture to strive for a substantial improvement on system performance. High-frequency spectrum communication technologies are increasingly used in 5G for faster data communication, but due to the limitation of high-frequency radio wave penetration capabilities, wired and wireless (including optical means) networking technologies are still the backbone of 5G networks.

Large-scale MIMO technologies will play a big role in 5G systems as it could offer the following important benefits: (1) its spatial resolution is significantly enhanced from existing MIMO for 4G which enables deep mining of spatial dimension resources to allow multiple users to communicate with the base station at the same time greatly improving the spectral efficiency without increasing the bandwidth; (2) it can concentrate the beam in a very narrow range, significantly reducing interferences; (3) the transmitting power can be markedly reduced to improve power efficiency; and (4) with enough number of antennas, it can make linear precoding and linear detector optimal and make the noise and uncorrelated interference negligible (Dai et al. 2015).

A filter bank-based multicarrier (FBMC) technology is used to improve the performance of OFDMA technology in 5G systems. This FBMC technology enables the flexible control of the bandwidth setting and the overlapping degree of each subcarrier, so that the interference between adjacent subcarriers can be flexibly controlled and that scattered spectrum resources can be easily used. Furthermore, there is no need for synchronization between subcarriers. Synchronization, channel estimation, and detection can be processed separately on each subcarrier, making FBMC especially suitable for uplink that often encounter difficulties in achieving strict synchronization between users. But on the other hand, because the carriers are not orthogonal to each other, there is interference between subcarriers. Additionally, due to the use of non-rectangular waveform, there is time-domain interference between symbols, which needs to be eliminated relying on certain technologies.

Full duplex communication technology refers to the technology of bi-directional communication that proceeds at the same time and with the same frequency. In wireless communication systems, both the network side and the terminal side have inherent self-interference of transmitted signal to the received signal. In the existing wireless communication system, due to technical limits, two-way communication with the same frequency cannot proceed at the same time. The two-way links are distinguished by time or frequency, each of which corresponds to TDD (time-division duplex) or FDD (frequency-division duplex). Caused by the failure to engage in simultaneous and same frequency two-way communication, half of the wireless resources (frequency and time) are wasted in theory. Since full duplex technology could, theoretically, double the spectrum utilization, it would allow more flexible spectrum utilization. Meanwhile, as device technology and signal processing technology mature, full duplex technology with the same frequency at the same time has gradually become a research focus and an important direction for 5G system in terms of making full use of wireless spectrum resources. However, full duplex technology is also faced with a number of challenges. The large power difference between receiving and transmitting signals leads to severe self-interference (typical value is 70 dB), and as such, the paramount problem for the application of full duplex technology is the cancellation of self-interference (Bian et al. 2013).

To increase data traffic capacity by 1000 times in 5G systems, technologies that reduce the cell radius, improve the spatial reuse rate of spectrum resources, and enhance the transmission capacity per unit area are required. However, owing to the decrease of cell coverage and the lack of optimal site location, further cell division is difficult to carry out, and the system capacity can only be improved by increasing the number of low-power nodes, which means the increase of site deployment density. According to relevant predictions, in future wireless networks, in the coverage area of the macro station, the deployment density of all kinds of low-power nodes of various wireless transmission technologies would be 10 times of the existing site deployment density, and the distance between sites will be 10 meters or even smaller, supporting up to 25,000 users per square kilometer. Moreover, the proportion of the number of activated users and the number of stations in the future would be 1:1, i.e., all activated users would be assigned with their own service nodes, thus building a super-dense heterogeneous network (Chen et al. 2016).

Although the super-dense heterogeneous network is deemed promising, due to the reduction of the distance between nodes, it would generate problems that differ from those generated by the existing system. In 5G network, there may be interference in the same frequency deployment between the same wireless access technology, interference in the shared spectrum, and interference between different coverage levels. How to cope with the damage to performance caused by these interferences and realize the coexistence of multiple wireless access technologies and multiple coverage levels is a critical issue that calls for in-depth studies. Due to the small difference of transmission loss between adjacent nodes, there may be multiple interference sources within similar intensity that lead to more severe interferences; hence, the existing interference coordination algorithm for single interference source cannot be directly applied to 5G systems. Due to the different QoS requirements based on different services and users, the key issues in ensuring system performance are the sharing of different services in the network, the coordination strategy between various nodes, network selection, the lowest energy efficiency cell activation, and energy-saving configuration strategy based on user requirements.

The adoption of complex wireless transmission technology and wireless network architecture in 5G systems makes its network management much more complicated than existing networks, and deep network intelligence is an urgent need to ensure 5G network performance. Therefore, ad hoc networks will emerge as a major technical support for 5G. The SON (Self-Organizing Network) technology can support automatic planning, configuration, management, optimization, and healing for deploying connected devices within a mobile radio access network. If this technology could be improved to make it capable of supporting collaboration between multiple networks, it would be useful in 5G systems (Liu et al. 2011).

3.3 IoT Network Technology

This section will introduce a few basic topologies often used for designing IoT networks, as well as a few network technologies often used to construct agricultural IoTs. Network topology refers to the shape of the network, or the physical layout of the network of interconnected devices, which is also a way of connecting devices in a network. The topology diagram illustrates the network configuration of the network servers and workstations and how they are connected to each other.

Before introducing these fundamental network topologies, it might be necessary to have a quick look at bus topology as it may be applied in some of these networks. In bus topology, all devices are directly connected to the bus with no central control device needed. Data sent by connected devices is broadcasted to the bus and is transmitted serially in the form of baseband. Each device connected to the bus uses a uniquely assigned address for performing data communication, in the same principle of CAN bus.

3.3.1 IoT Network Topologies

The term "topology" comes from geometry. Network topology refers to the method of studying the relationship between points and lines, independent of size and shape, in structure. The computer and communication equipment in the network are abstracted as a point, and the transmission medium is abstracted as a line, and the geometry composed of points and lines is the network topology. The topological structure of the network reflects the structural relationship of the entities in the network, which is the first step of constructing the network, and the foundation of enabling multiple network protocols. Additionally, the topological structure exerts a significant impact on network performance, system reliability, and communication costs.

3.3.1.1 Star Network

Figure 3.13 illustrates a very commonly used network structure, the star network, which refers to a network of workstations connected in a star mode. The network has a central node, and other nodes (workstations and servers) are directly connected to the central node. A star topology is centered on the central node with multiple workstations individually connected to it. This is one of the oldest forms of network topology, and today's telephone also adopts the star topology. At present, star topology with extensive structure is one of the most common network topology designs and widely used in the design of general network environment (Guan and Xia 2018).

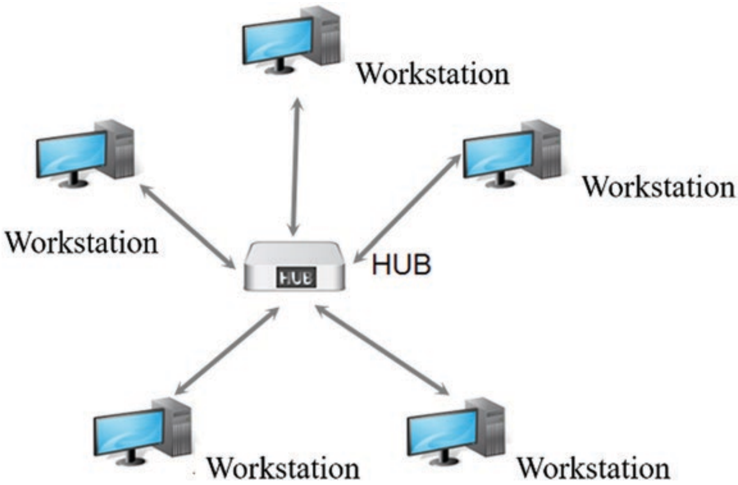

Fig. 3.13 Topological diagram of a star network

Communication between any two nodes in a star network is controlled by the central node, often called the HUB. Therefore, the main functions of the central node are (1) checking the availability for accessing, if it is then connecting to the calling station; (2) maintaining a secured connection for the channel during the course of communication; and (3) disconnecting the channel as soon as the communication is completed or is confirmed a failure to make the access available for the next caller.

Star network topology has been widely used in existing data and voice communication networks. For example, the Private Branch Exchange (PBX), i.e., “telephone exchange,” is built in a star network topology. As an important branch of local area networks, PBX could provide integrated voice and data communication within the network in addition to regular voice communication and teleconference services.

Communication between end users in a star network must pass through the central node, which is easy to construct, control, and maintain with high security. A star network will not affect the communication between other end users even if the equipment malfunctioned at one user’s end. In addition, the network delay time is short, and the rate of transmission error is low. One of the major disadvantages of this structure is that the central system must be highly reliable, because if this system malfunctioned, the whole system would collapse. To improve the reliability of the system, the central system usually adopts double machine hot backup, which drives up the cost accordingly. In addition, the communication between any two nodes in the star network must pass through the central node. Therefore, the central node carries much heavier burden heavier than any other nodes, which once again requires the central node to be highly reliable.

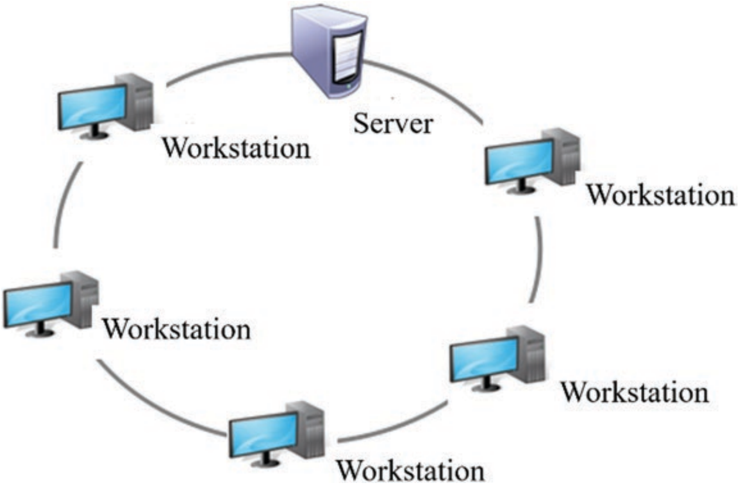

Fig. 3.14 Topological diagram of a ring network

3.3.1.2 Ring Network

Ring topology is a network topology connecting all nodes in a ring structure (Fig. 3.14) which transfers data from one node to another. This structure enables the public transmission cable to form a loop connection, where data is transmitted from node to another along one direction in the loop and therefore without the need of having a central system. Ring topology is primarily adopted in token networks, where each device is connected through cables directly to form a closed loop, and the information sent by the whole network is transferred in this loop. Because of that, such networks are also called “token ring network.” As a matter of fact, the ring network does not mean that all nodes must be connected to a physical ring. In general, those nodes can be virtually connected to the ring by an impedance verifier without the geographic limitation of the physical locations of these nodes.

The major characteristics of a ring network include the following: (1) it has a standard topological design specified by IEEE 802.5 token ring network, where “tokens” (transferred data) are passed in turn in ring structure connected using a coaxial cable; (2) it has a relatively fast transmission speed (16 Mbps allowed in token networks); (3) each node is connected with two adjacent ones with a one-way loop transmission for data communication; and (4) reliability could be low as all nodes are directly connected in series where one node failure can cause the interruption and paralysis of the whole network.

Such characteristics make ring networks (1) fairly simple to implement as all nodes are connected in a ring without needing expensive node-set devices such as hubs and switches and (2) subject to bootstrap control; thus, the control software is simple. However, as the information source passes through each node serially in the loop, the transmission rate is bound to be affected if too many nodes are in the loop which will in turn delay the response time. Furthermore, the structure could be difficult to reconfigure as the ring is close and addition and/or removing requires interrupting the entire system to reconnect adjacent nodes which also make it difficult to maintain.

3.3.1.3 Mesh Network

Figure 3.15 illustrates the topological structure of a mesh network, which refers to a network in which all nodes are connected to each other through a point-to-point transmission link with each node connected to at least two other nodes, and therefore it is also called a distributed structure. Mesh network is generally used in Internet backbone network, and routing algorithm is used to calculate the best path to send data.

In a mesh network, several subnets can be connected using bridges, routers, and/or gateways with each subnet having hubs and repeaters to connect multiple devices. To provide such a function, a mesh network often consists of three topological structures: (1) the mesh topology used to forming the network which optimizes the route for the fastest possible data transmission between connected nodes and allows the network to be connected to a larger network; (2) a backbone topology for connecting subnets using a single bus or a ring topology via a bridge and a router; and (3) a start topology for connecting devices in subnets.

The major advantages of a mesh network include (1) high reliability as it provides at least two communication paths between any two nodes; (2) allowing nodes within the network to share resources easily; and (3) choosing the best path for the condition to minimize transmission delays. Such advantages are often paid the price of (1) being burdened by complex software which may lead to more difficult to

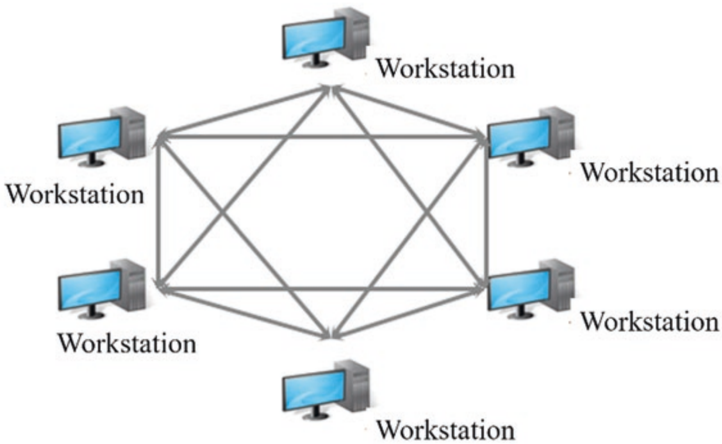

Fig. 3.15 Topological diagram of a mesh network

control, manage, and maintain; and (2) the line system could be complicated and difficult to expand, in addition to being costly.

3.3.1.4 Tree Network

Tree topology (Fig. 3.16), an evolution from bus topology, is shaped like an upside-down tree with a root at the top with branches, each of which can extend into sub-branches. Tree topology is a hierarchical centralized control network. Compared with the star topology, the total length of its communication lines is short, the cost is low, the nodes are easy to expand, and it is convenient to find the path. However, in addition to the leaf nodes and their connected lines, the failure of any node or its connected lines will affect the system as a whole (Zhang et al. 2016).

The major advantages of a tree topology include (1) easy to expand as this structure can be easily extended to many branches and sub-branches and (2) easy to isolate faults within the branch or node that experienced a failure. The main disadvantage of this network is that nodes are heavily dependent on the root node. If the root node fails, the whole network fails.

3.3.1.5 Hybrid Network

A hybrid topology is a type of network topology that combines two or more differing network topologies. A couple of commonly used designs include "star-bus" topology and "star-ring" topology. Taking a "star-bus" hybrid topology (Fig. 3.17) as an example, this network topology could satisfy the need for expansion into larger network and eradicate the limitation of star topology in transmission distance and the limitation of bus topology in the number of connected users. This network topology carries the advantages of both star topology and bus topology and can compromise for their disadvantages in some degree.

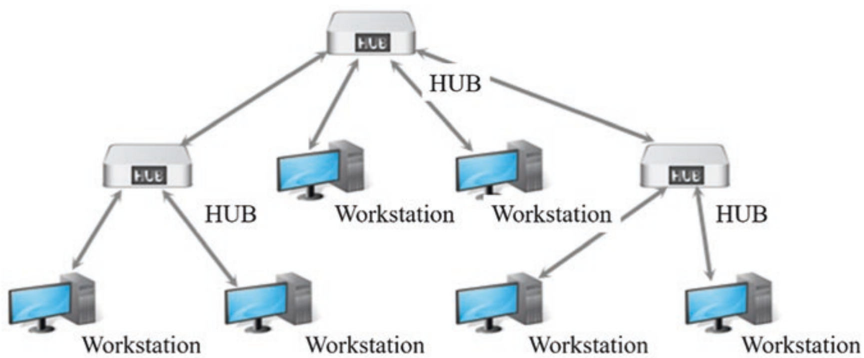

Fig. 3.16 Topological diagram of a tree network

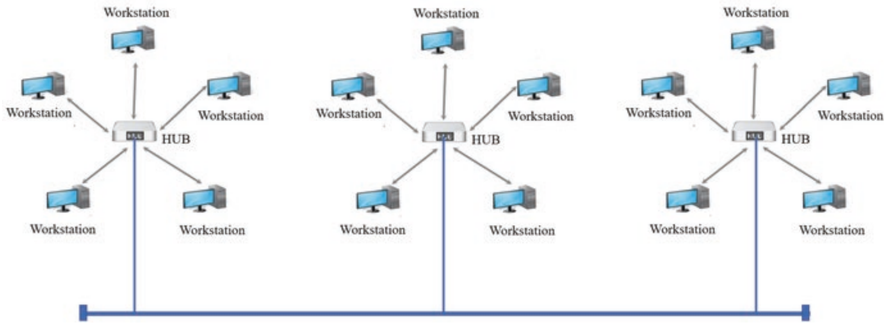

Fig. 3.17 Topological diagram of a star-bus hybrid network

This type of hybrid network topology is often used for relatively large LAN applications. Assuming that an enterprise has several locations that are distant from one another (yet in the same community), if a star network topology were used to construct the enterprise LAN, it would be difficult as there is a limitation on transmission distance for any single node, e.g., about 100 m, when a twisted pair is being used in the star network. Similarly, if bus topology were used, it would be unable to support the total number of nodes that need to be connected for the enterprise. By combining these two, it could apply a star topology to connect nodes nearby and use the bus topology to connect star networks distance away. The transmission medium can be selected differently in terms of the distance being connected: if the distance is relatively close (<500 m), coaxial cable could be preferable; otherwise, fiber-optic cable could be more suitable (Yi et al. 2018).

Hybrid topology has the following characteristics: (1) having wide applications as it can help to overcome some shortcomings of individual topologies (however, some disadvantages of particular topology will be carried (e.g., the network speed would decrease with the number of nodes being increased when a bus topology is involved)); (2) easy to extend if a star or tree topology is involved; (3) may still have some disadvantage of bus topology; (3) often faster as it could use high-speed medium for constructing its backbone network; and (4) relatively difficult to maintain as it will make the combined topology more complex than their individual structure as it often requires taking consideration of the features of composing topologies in maintenance. If the bus is broken, the whole network will be paralyzed, but if the branch network segment fails, the normal operation of the whole network will not be affected. Additionally, the network is very complex and difficult to maintain.

3.3.2 Zigbee Network Technology

3.3.2.1 Overview of Zigbee Technology

Zigbee is a low-rate wireless personal area network (LR-WPAN) technology specified by IEEE 802.15.4. The word "Zigbee" comes from the waggle dance of honey bee which honey bees used to communicate the location information, such as the direction and distance, with other honey bees. People borrowed this term to name a short-range wireless communication technology of low power, low data rate, long battery life, and low cost (Li 2016). Zigbee standard was developed by Zigbee Alliance, formed in 2002 as a nonprofit organization by many major companies like Philips, Mitsubishi Electric, Epson, Atmel, Texas Instruments, etc. Philosophically similar to CAN protocol, Zigbee protocol specified by IEEE 802.15.4 standard defines only the physical (PHY) layer and the medium access control (MAC) layer and allows users to define their own network and application layers.

Zigbee technology is suitable for two-way communication between sensors and control system. It supports low data rate of about 250 kbps, with wireless communication distance of 10 to 100 m using operating frequencies of 868 MHz, 902 to 928 MHz, and 2.4 GHz. Zigbee technology has been commonly used in many short-range communications for automation, such as smart homes, industrial automation, and medical monitoring applications, and has also found a wide range of applications in agriculture.

A Zigbee communication system is usually composed of three types of devices, i.e., coordinator, router, and end device. Every Zigbee network must have at least one coordinator which acts as the root and bridge of the network and buffers wireless data packets for sleeping end devices so it cannot sleep itself, and therefore it is a full function device (FFD) in a Zigbee network. Router is also an FFD in a Zigbee network and can join the network to send, receive, and route data. Like a coordinator, it can also buffer wireless data packets for sleeping end devices and therefore cannot sleep. Such a functionality makes router acting like an intermediary device for data transmission, and it may have multiple routers or even none in a Zigbee network based on its topological design. The end device can only send or receive data from either a coordinator or a router but not directly from each other so it is a reduced function device (RFD) and can join the network via either a coordinator or a router. However, it can have a planned sleep mode to enter a temporarily non-responsive status for saving energy and suitable to be used as a remote node to link sensors or controllers to a network. A Zigbee network can theoretically have any number of end devices.

As aforeexplained, a Zigbee network can be composed of one or more coordinator, zero to a few routers, and multiple end devices. The number of coordinators, routers, and end devices depends on the type of network, such as star or mesh networks. In a star network arrangement, the end devices can directly join the network through the coordinator, and in a mesh arrangement, routers will be necessary for connecting end devices to the coordinator (Fig. 3.18).

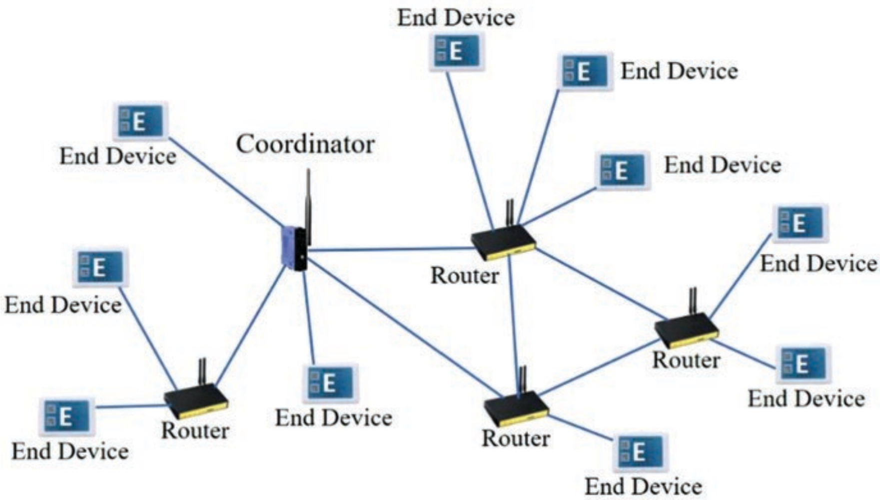

Fig. 3.18 Mesh topology arrangement of a Zigbee network

3.3.2.2 Initialization of Zigbee Networks

The establishment of Zigbee network begins with the network coordinator, and only FFD can be used as the coordinator. In establishing a network, the FFD node shall send a beacon signal to request command through "active scanning" and then set a deadline for a scan. It will allow the FFD to be established as a coordinator for a Zigbee network, if there were nodes being identified and communication being initialized within the coordinator's wireless point of sale (WPOS). If no responding beacon signal could be detected during the scan period, it could be considered that no nodes were found within the scope of its WPOS and no network communication could be initialized. After the coordinator is established, the coordinator begins the channel scanning process, including "energy scanning" and "active scanning." First, the energy of the specified channel or the default channel should be detected to avoid possible interference. The channels at the allowable energy level are selected and marked as available channels, and the channels with energy value exceeding the allowable level are discarded. Then active scanning is performed to search network information within the communication radius of the node. This information is broadcasted in the network in the form of beacon frames that are made available to the nodes through active channel scanning. Based on this information, the optimal and relatively quiet channel can be identified. According to the results, the channel that has the least Zigbee networks or preferably no Zigbee equipment can be chosen. During active scanning, the MAC layer of the Zigbee network dismisses all frames received by the PHY layer data service except the beacons. If the application needs to establish a network on a specific channel, then the working channel range of the network can be limited to the specified channel, and a low threshold can be set (Lv 2008; Xie and Deng 2016).

As aforementioned, in a start network, end devices (nodes hereafter) are connected directly to the coordinator. In this process, a new node needs to first actively scan the surrounding network and send beacon request for connection after finding the network. When the coordinator detects the beacon request, it will send a beacon message to establish the connection. If the appropriate network is not detected, the node will re-scan at intervals. Data transfer between coordinator and nodes can be done using beacon-enabled method. In beacon-enabled networking, the coordinator allocates a time slot to each end device, known as the guaranteed time slot (GTS), and the clocks of all nodes connected to the network need to be synchronized, through sending a beacon signal from the coordinator to each node. Once a node is synchronized, it can transmit data to the coordinator using carrier-sense multiple access with collision avoidance (CSMA-CA) method, commonly during the GTS allocation period. For the transfer of data from a node to the coordinator, it will first send a request to the coordinator via a beacon message, and the coordinator will reply with a confirmation message to start the transmission (Rohde et al. 2014). For the transfer of data from the coordinator to a node, the coordinator will send the beacon message to the node and start transmitting data after receiving a response from the node. If a communication channel could not be conformed (i.e., no responding message being sent back), then the data to be transmitted to the node will temporality stored in the coordinator, and wait for the next GTS for trying again to deliver the data.

The data transmission can also be initiated in a non-beacon-enabled method, by which the coordinator will not transmit any beacon message. For the transfer of data from a node to the coordinator, each device will transmit data using CSMA-CA method as soon as the channel is clear. For the transfer of data from the coordinator to a node, the same process as beacon-enabled method will be used, but with the use of a data request message instead of beacon signal.

When at least one router is used in a Zigbee network under a mesh topology, it can use one of the two ways to link a node to the network: either use a router as the bridge to get an associate access in which the node is added to the router (can also be called the parent node) as a child node or get a direct access to the coordinator like in a start topology we have just discussed. The associate access is the primary way for new nodes in Zigbee network to join the network. If the node were connected as a child node, it would have information about the parent node in its association table; thus, it can send the request to join the network directly to the parent node. If the parent node has the authority to allow a direct entry to the coordinator, then it will be assigned a network address for it to be able to join the network. If the number of child nodes in a parent node's network reached its maximum limit, it will allow a node to be connected via other parent nodes or even directly to the coordinator if there is a channel available to join the network as a new node.

Similar to operating in a star network, for a new node, it will first scan for networks around it through active or passive scanning on one or more channels being set up in advance. Then the node will look for an optimal parent node capable of approving its entry into the network and store the information of the parent node that can be identified into its association table. The data stored in the parent node of the association table includes the Zigbee protocol version, the specification of the protocol stack, the PAN ID (personal area network ID), and the information that can be added. The new node will select the one with the lowest depth from all the parent nodes in the association table and send a request to it. If more than two parent nodes with the same minimum depth appear, then it will randomly select one to send a request. If the request is approved, the parent node will assign a network address at the same time. If the network is successfully accessed at this point, the child nodes can start the communication, and if the request fails, it will look up the association table again and continue sending requests until it joins the network.

After the appropriate channel is identified, the coordinator sets the remaining network parameters, including the network identifier (PAN ID), network address, and extended PAN ID. PAN ID is a randomly generated 16-bit identifier that should not be 0xffff (which is reserved as the broadcast PAN ID) and must be unique in the channel that is used and must not conflict with other nearby Zigbee networks. There are two address modes in Zigbee networks: extended address (64 bit) and short address (16 bit). The extended address is assigned by the IEEE organization for unique device identification, while the short address is used for device identification in the local network. In a network, the short address of each device must be unique. It is assigned by its parent when the node joins the network and communicated using the short address. For the coordinator, the short address is usually set to 0x0000. The extended PAN ID can be set by the network layer attribute nwkExtendedPANId in advance. When these parameters are set, the network initialization process of the coordinator is finished.

3.3.2.3 Performance of Zigbee Networks

A series of parameters is defined to provide a quantitative measure of overall performance of Zigbee networks, so that users can have a more precise understanding of how a network performs in real operation. These quantitative parameters describing the performance are called the measurement indicators, and a few most important ones are briefly discussed below.

Low Data Rate Zigbee is a wireless transmission technology with low data rate. Its maximum data transmission rate is 250 $kB{\cdot}s^{-1}$, but this is just the rate on the link; after removing the frame head cost, channel competition, reply, and retransmission consumption, the real rate that can be used for application may be less than 100 $kB{\cdot}s^{-1}$. Furthermore, this rate is used by multiple nodes and sometimes multiple applications on the same node; therefore, it is not suitable for transmitting large amount of data, but just sufficient for being used in sensing and control.

Reliability Zigbee adopts spread-spectrum technology in its PHY layer, which allows it to resist interference to some extent. Moreover, its MAC application layer (APS part) features response and retransmission functions, and the CSMA mechanism in MAC layer allows the node to examine the channel before sending to avoid interference. When a mesh network is adopted in the network layer, there will be multiple paths from the source node to the destination node; such path redundancy strengthens the robustness of the network it allows rerouting if a malfunction is detected in the original selected path to ensure the communication is being continued and completed.

Delay Delay is an important measure of network performance. As Zigbee relies on random access to connect to the MAC layer and does not support TDM channel access, it cannot well support some real-time services. Moreover, sending conflicts and multiple hops makes it difficult to determine delay.

Power Consumption In general, the application rate carried on Zigbee nodes is low in most cases. When there is no need to communicate, the nodes can enter a sleep mode with very low power consumption to a level of a few thousandth of that consumed in normal working state. As the normal working time normally counts for a small portion of the total running time, sometimes even less than 1%, thus insert of a sleep mode in end devices could substantially improve the energy efficiency and allow the battery life to last for a year or 2. Zigbee nodes can easily switch between hibernation and normal operation, which may take only a few milliseconds.

Networking and Routing Features Zigbee is superior in terms of these features that belong to the network layer. The first is large-scale networking capability; Zigbee can support up to 65,000 nodes per network, whereas Bluetooth can only support 8 nodes per network. This is because Zigbee's bottom layer uses direct scaling technology and the network can expand significantly if non-beacon mode is used as synchronization is not required. And it is also quick for the nodes to join and rejoin the network, generally within 1 s or even faster, while Bluetooth usually takes 3 s to achieve the same. In terms of routing, Zigbee supports the routing of highly reliable mesh network; thus, it can lay out a wide range of networks and achieve multicast and broadcasting, providing robust support for various applications.

3.3.2.4 Applications of Zigbee Technology in Agriculture

In short-distance wireless communication, Zigbee and RFID, which emerged relatively late but have rapidly grown, are increasingly used in agriculture application. Figure 3.19 shows an example of a low-cost wireless agricultural sensor network and data transmission system developed based on a single-chip microcomputer and Zigbee chip. In this Zigbee-based wireless sensor network, the sensed data was wirelessly transmitted to communicate with an in-office monitoring and control system which can also provide decision support and database management at the same time for automatically and effectively regulating field operations.

RFID, a non-contact method of automatic identification technology, has also found a huge application potential in agriculture, such as livestock tracking, agricultural produce traceability tracking, and agricultural logistics identification. It has also been increasingly used as wireless tag for field sensors for providing the location and other relevant information of those sensors and as end devices in a Zigbee wireless field sensor network.

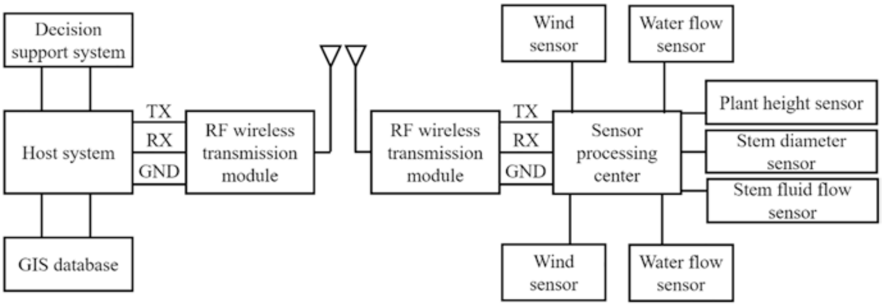

Fig. 3.19 System block diagram of a wireless information transmission system developed for real-time field sensing and monitoring

3.3.3 LoRa Network Technology

3.3.3.1 Overview of LoRa Technology

LoRa (Long Range) is a low-power wide area network (LPWAN) protocol developed by Semtech Corp, a US high-tech company making high-performance analog and mixed-signal semiconductors and advanced algorithms. In the past a couple of decades, with the rise of IoT technology, the need for accessing remote IoT devices quickly increased, and the LPWAN access technology was created for meet this need. This technology, adopting star network coverage, has the advantages of long transmission distance, low operation power consumption, and low operation and maintenance cost. LoRa protocol, one of the mainstream LPWAN technologies, is suitable for scenarios where only a small amount of data needs to be transmitted. It is derived from chirp spread-spectrum (CSS) technology, which not only reduces the communication power consumption but also increases the communication distance, thus transforming the previous way of the trade-off between transmission distance and power consumption. LoRa protocol is developed on the basis of spread-spectrum communication which allows LoRa devices to have large communication capacity. Another important feature of this technology is that even if the same frequency were used in different terminals, those devices would not be interfered with each other and could receive and process data of multiple nodes in parallel. This technology, adopting forward connection error (FCE) technology obtaining error control in data transmission by sending redundant data and recognizing only the data portion without error, can keep the error rate in wireless data transmission at a very low rate to improve the robustness of the network (Dong and Huang 2017).

LoRa technology defines the PHY layer of a LoRa network system. The LoRa protocol works in the free RF bands, such as 868 MHz in Europe, 915 MHz in North America, and 923 MHz in Asia. Integrated as proprietary spread-spectrum modulation and FEC technologies, LoRa enables an ultra-long transmission distance (more than 10 km) with a very low power consumption (battery life up to 10 years). With the introduction of the new version of LoRa technology in 2018, the capability and performance are further improved.

To cover the upper layers, other technologies and protocols are needed. LoRaWAN, one of the protocols to fill this gap, defines the communication protocol and system architecture for the network layer and manages the communication between LPWAN gateways and end devices. LoRaWAN is also maintained by the LoRa Alliance, an open nonprofit technology association consisting of more than 500 members to promote IoT LPWAN technologies.

3.3.3.2 LoRa Network Architecture and Protocol

Figure 3.20 illustrates a conceptual LoRa network consisting of four groups of components: end devices (or nodes), the group of devices with an embedded low-power LoRa communication module build-in; the gateways (or the base stations/connectors) which connect end devices to the Internet by bi-directionally transmitting data to and from the end devices; network servers which route messages from end devices to the right application and back; and applications which are software programs for specific purposes running on application servers or on cloud.

LoRa network is a type of WAN designed to wirelessly connect battery-operated devices to the Internet addressing the core IoT requirements, including bi-directional communications, end-to-end security, and mobile and static location recognition services. It provides a seamless interoperability among smart devices without the need of complex local configurations, hence empowering users, developers, and businesses in IoT (Zhao and Su 2016). The LoRaWAN network architecture is a typical star topology in which the LoRa gateway is a transparent transmission relay that connects the terminal device to the back-end central server. The gateway is connected to the server via standard IP, and the terminal device communicates with one or more gateways over a single hop. All nodes communicate with gateways in a two-way manner, and operations such as cloud upgrade are also supported to reduce cloud communication time.

Communication between the end devices and the gateway is accomplished on the basis of different frequencies and data transmission rates, and the selection of data rates requires a trade-off between transmission distance and message delay. Because of the adoption of spread-spectrum technology, communications at different transmission rates do not interfere with each other, and a set of "virtualized" bands is created to ramp up gateway capacity. The data transmission rate of LoRaWAN ranges from 0.3 kbps to 37.5 kbps. To maximize the battery life of the terminal device and the overall network capacity, the LoRaWAN network server controls the data transmission rate and the RF output power of each end device through an Adaptive Data Rate (ADR) scheme (Zhao and Su 2016).

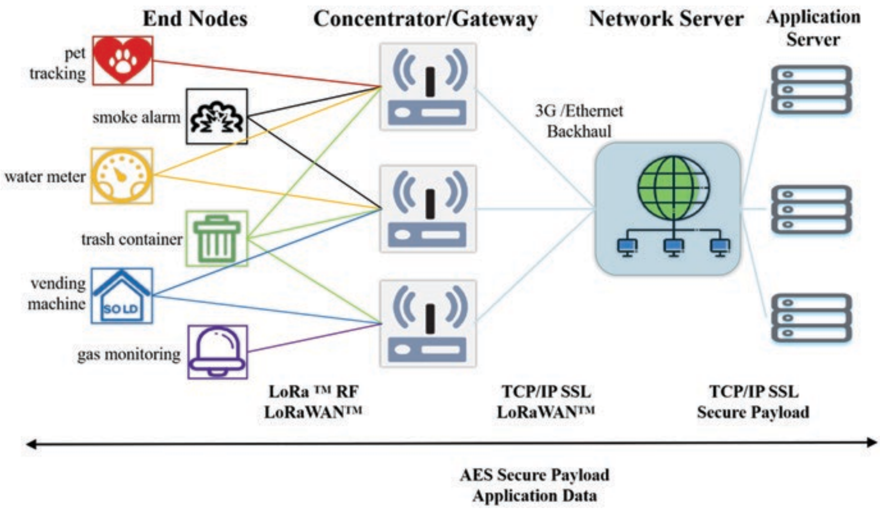

Fig. 3.20 LoRa network composition

3.3.3.3 Applications of LoRa Network in Agriculture

Many successful development and applications of LoRa network in agriculture applications are being reported in the past decade. This section briefly introduces three applications to different aspects of agricultural production, just as an illustration on how agricultural production can gain benefits from adopting this technology.

Greenhouse Monitoring

Star topology structure is often selected for building greenhouse IoT monitoring systems as it is often characterized by simple structure and low power. In theory, a single parent node can hold up to 300 000 end nodes in a LoRa network. Supported by the long-range accessibility, the installation location of end nodes and sink node can be flexibly arranged in a case-specific manner. This design could satisfy the IoT communication requirements for most agricultural greenhouse applications.

According to the environmental characteristics of agricultural greenhouse, this system adopts lithium battery as the power supply and gives priority to power consumption and performance in device selection and hardware and software design. At the same time, it is essential to reasonably control the power consumption of all equipment and prolong the life cycle of monitoring network. LoRa technology, the core of this system design, is used to increase the communication distance of nodes, reduce the number of deployment of relay nodes, and provide data communication services for the star network composed of acquisition nodes and sink nodes. In the complex environment of large agricultural greenhouse, LoRa technology made this system achieved a secure communication radius over 2 km. Structurally, this system is composed of three layers: (1) perception layer, composed of various sensor acquisition nodes placed at different locations to collect representative data and transmit the data to the application layer for supporting management; (2) transmission layer, where LoRa technology (or combined with mobile communication networks) can be used for data transmission from data node to sink node and from sink node to user management node; and (3) application layer, used to receive the data sent by the lower end module and to determine whether the current greenhouse environment is suitable after storage and analysis. If not, it will issue science-based warning. For example, if the temperature in the greenhouse is too high, it will start the alarm and indicate that cooling equipment can be used; if the temperature is too low, it will turn on the heating equipment; and if soil moisture is insufficient, it will start the irrigation equipment, etc.

Farmland Environment Monitoring

Farmland environment monitoring system, when developed based on a LoRa network, enables automatic monitoring and remote transmission of soil, micrometeorology, and water quality information from remote fields. Depending on the core parameters to be sensed, farmland environment monitoring systems can be categorized as soil moisture monitoring stations, field microclimate monitoring stations, hydrology and water quality monitoring stations, etc. Higher-scale farmland for comprehensive monitoring of ecological environments can also be established to collect soil, weather, and water quality parameters simultaneously. The monitoring station features low power consumption and integrated design, and the power supply comes from solar energy, which is a green product. Moreover, it comes with superior tolerance against extreme farmland environments and certain anti-theft property.

Numerous wireless sensor networks based on LoRa networking technology have been designed for being practically usable in actual field environments. Such systems deploy wirelessly connected sensor nodes to collect farmland environment data, send the sensed data to application servers via LoRa network for analyzing and storing the data, and issue timely notification when data go beyond preset thresholds. It allows the management staff to make decisions and send control signals to relevant control nodes to adjust relevant parameters if applicable, thus achieving remote monitoring and control. Take a farmland meteorological monitoring system as an example, and such a system often consists of three subsystems.

The meteorological data acquisition subsystem is primarily created to perceive all needed data for monitoring micro-meteorological changes at a specific farmland. The most commonly used sensors include air temperature and humidity sensor, soil moisture and temperature sensor, light sensor, etc. The data transmission subsystem often uses LoRa network technology to transmit the collected field data from field sensor nodes to a networked computer for data processing. The implementing equipment connected to this system includes devices and/or facilities used to adjust the microclimate of a specific field, such as irrigation equipment. This subsystem is used to implement management decisions automatically through regulating operations of relevant equipment. Oftentimes, such a control is simply turning the equipment on or off remotely using the wireless networking technology.

Facility Agriculture
Facility agriculture refers to a farming method which conducts the production within a constructed facility to create favorable conditions to increase the productivity and improve the produce quality. It is an important mode of development in modern agriculture, and it played an increasing role in improving the ecological function. As it involves a lot of monitoring and controlling functions to operating an agricultural facility, it provides probably the best application scenario for adopting IoT technologies in agricultural production. The functions needed for an IoT-based facility management system will include comprehensive situation perception, reliable data transmission, intelligent decision supports, and automatic implementation of all equipment controls. A typical agricultural IoT-based agricultural facility monitor and control system normally consists of three functions: productional scenario perception, networked data transmission, and intelligent data processing.

The production scenario perception often include the monitoring and recording of six scenario indicators of water, fertilizer, electricity, heat, gas, and light through sensing soil, water, plant, microclimatic, and light data at adequate intervals to maintain an optimal and stable growing environment of crops in the facility.

Networked data transmission plays a crucial role in such an IoT system. Under normal circumstances, monitor of environmental parameters and crop growth in a facility is completed through relevant end devices installed in the facility. The collected sensor data and processed control signals are transmitted via the bi-directional network transmission.

The intelligent data processing could include near-real-time data-based crop growth simulation at an application server to find out optimal control strategies for achieving the best possible outcomes from the production. Such an application server could also perform other decision-making analysis to provide automatic control of related equipment, such as that used for light, temperature, and water control in the facility.

3.4 Narrowband Communication Technologies

The term "narrowband" refers to the channel bandwidth for RF communication, and it is relevant to "broadband." Based on a definition used by the European Telecommunications Standards Institute (ETSI), narrowband (NB) refers to those channels with a communication bandwidth of 25 kHz or less. For those with its channel bandwidth further narrowing down to 100s, or even 10s, Hz are usually defined as the ultra-narrowband (UNB). The primary benefit of using narrowband in communication is the lower noise bandwidth and hence better sensitivity and range which fits the need for many IoT systems; therefore, it is attractive for IoT applications. This section provides a brief description of NB- and UNB-IoT technologies and their applications.

3.4.1 *Narrowband (NB) IoT*

3.4.1.1 NB-IoT Technology Overview

Narrowband IoT (NB-IoT) is a technology standard of RF communication for IoT, developed by the 3rd Generation Partnership Project (3GPP) standards organization and called LTE-M (Long-Term Evolution Machine-Type Communication). In September 2015, the International Telecommunication Union (ITU) officially announced its IoT standard and changed the term LTE-M to narrowband IoT (NB-IoT). Because of its characteristics of low power consumption, stable connection, low cost, and outstanding structure optimization, NB-IoT has drawn much attention since then. One noteworthy advantage of NB-IoT is that it can coexist with existing network technologies and therefore allows having a smooth upgrade to many existing IoT networks. Furthermore, this technology can also be applied to the GSM network and LTE networks (Min et al. 2017).

A NB-IoT network is typically constructed by terminals (end devices), base stations, the core network, M2M (machine-to-machine) platforms, and application server. Terminals mainly include sensors, IoT chips, and embedded software. NB-IoT base station allows three modes of deployment: independent deployment, protection zone deployment, and in-band deployment. Independent deployment means that NB-IoT is deployed in a separate 200 kHz spectrum and there is a vacant spectrum of 895 kHz between 879.105 and 880 MHz. In protection zone deployment, NB-IoT is at 850 M frequency band. Under 5 M bandwidth in LTE, the single side protection band is less than 250 k, which does not meet the deployment conditions. Protection zone deployment is possible in 1800 M band under LTE 15 M and 20 M bandwidth configurations. In-band deployment refers to the scenario when NB-IoT is deployed in LTE band.

Different from the existing core network, the NB-IoT core network features main functions that include mobility, security, connection management, soft SIM access, delay insensitive terminal adaption, congestion control and flow scheduling, charged use, etc. Additionally, related entities include mobile management entities connected to the IoT, service gateways, PDN gateways, etc. The main functions of M2M platform include application-layer protocol stack adaptation, terminal SIM OTA, terminal equipment, event subscription management, API capability opening (industry, developer), OSS/BSS (self-service account opening and billing), big data analysis, etc. The M2M platform is application-level equipment without unified standard, and each company can customize the technical specification of the M2M platform according to its own needs.

3.4.1.2 Technical Features of NB-IoT

The main technical features of NB-IoT are explained here:

- Narrowband: the uplink bandwidth (3.75 kHz or 15 kHz optional); two modes (monophonic or polyphonic); downlink, OFDMA (occupying 200 kHz bandwidth, 10K protection band on both sides, actually occupying 180 kHZ); subcarrier number, 12; subcarrier bandwidth, 15 kHz.

- Low rate: uplink peak rate of 5.6–204.8 kbps and downlink peak rate of 176~234.7 kbps. The upstream speed is divided into 3.75k single-tone, 15k single-tone, and 15k multi-tone, while the downlink speed is divided into independent base station, protection zone base station, and in-band base station.
- Low power consumption: in power saving mode (PSM), terminals are still registered in the network, but the signaling is not reachable, so that the terminal can stay in deep sleep for a long period of time to save power. The eDRX further extends the sleep cycle of the terminal in idle mode, reduces unnecessary startup of the receiving unit, and significantly improves downlink accessibility compared to PSM. Under typical conditions of application, one AA battery could work for 15 years, hence meeting the requirements of most IoT application scenarios.
- High capacity: according to simulation test data under typical business model in TR45.820, a single cell can support 50,000 NB-IoT terminal access.
- Wide coverage: wide coverage is enabled by increasing narrowband power spectral density and retransmission times (could be up to 16 times), and by improving coding, total gaining up to 20 dB.

3.4.2 Ultra-Narrowband (UNB) Technology

3.4.2.1 UNB-IoT Technology Overview

UNB is initially defined as a technology capable of providing high spectrum utilization with at least 60 bits·s^{-1}·Hz^{-1}. When the technology was first proposed at the end of the last century, many were skeptical. After a few years of development, UNB was found far surpassed what was known about communication systems. For example, if a frequency band utilization rate were expected to be 100 bits/s/Hz, the energy ratio between signal and noise required to transmit each bit of information using UNB technology will be 281 dB; none of the current communication technology can reach such high power rates. However, it is very difficult, if not impossible, to realize ultra-narrowband communication using traditional communication theory and classical information theory. One example is that to achieve high bandwidth utilization, digital signal modulation must be improved to analog channel efficiency (Xu and Dong 2008).

UNB technology can solve this problem. When considering the extreme case of a narrowband in which the signal spectrum is compressed to a non-zero spectral line with a high concentration of energy, in this case, the theoretical bandwidth is zero, and the time-domain waveform must extend indefinitely to a pure sine wave, which cannot transmit any useful information. The analysis indicates that if the frequency of a sine wave remains unchanged and its waveform (amplitude, phase, shape or symmetry, etc.) dims slightly, the spectral energy is still highly concentrated in the carrier frequency, but the continuous spectrum corresponding to the random dither will appear on both sides, and the discrete spectral line will also appear at the harmonic of the carrier frequency. Because the jitter of waveform is fairly small, the energy of continuous spectrum and harmonic discrete spectrum is much lower than that of carrier frequency (tens of dB lower in ultra-narrowband). If the small jitter of the carrier waveform is controlled using useful information, that is, the maximum compression of the spectrum is used for transmitting information, a reduced frequency communication in sharp contrast to spread-spectrum communication should be produced. The purpose of frequency reduction is to achieve ultra-narrowband transmission, and the pursuit of digital transmission is the highest possible digital rate, but if backward technology is adopted, broadband may not be able to achieve high-speed data transmission. This brings a concept of fair assessment indicator: the band utilization rate. The bandwidth utilization rate of traditional digital communication technologies is much lower than that of UNB technology.

Along this line of thought, Walker (1997) developed a method using variable phase shift keying (VPSK) and variable minimum shift keying (VMSK) modulation to get the bandwidth efficiency needed for UNB communication. It demonstrated a superior performance of T1 bit rate transmission (a measure of digital transmission rate equivalent to 1.544 Mbit/s) with standard cellular time slot at bandwidth of 30 kHz, and the frequency band utilization rate exceeded 50 bit/s/Hz. Recently, the experimental VMSK modulation technology has been able to reliably transmit 270 kbps data in 2 kHz filter bandwidth. It was also reported that a 431 MHz UHF station realized data transmission of 1.7 Mbps, with the transmission signal bandwidth of 1 Hz, the receiving filter bandwidth of 2 kHz, and the spectrum utilization rate of above 1000 bit/s/Hz. With such breakthroughs, UNB technology will be critical to solving the contradiction between the shortage of wireless spectrum resources and the demand of system capacity (Wicks et al. 2006).

3.4.2.2 Technical Features of UNB-IoT Technology

Other than the low power consumption and other common technical advantages of NB communication, another major advantage of UNB technology is the low cost which is mainly resulting from an innovation for allowing merely update software on existing chips used for many transmission networks to meet the special requirement for UNB.

As any other technologies, while UNB achieved many technical advantages, it unavoidably has a few technical limitations with the major ones including limited terminal communication capacity, unguaranteed communication quality, unsafe empty entry, self-built network, limited downlink transmission capacity, and inability to support software update. The limited terminal communication capability is primarily caused by unauthorized spectrum. For example, the European regulations require that the duty cycle of each terminal in the 868 MHz spectrum must be less than 1%. Each data transfer will last around 6 s; thus, up to 6 messages can be sent per hour and 144 messages per day. In addition, as the unauthorized spectrum is not regulated, mutual interferences mean that the communication quality and reliability cannot be guaranteed. Also, because air interface technology is quite simple, effective encryption authentication is almost impossible; thus, there is a risk that data will be eavesdropped and cracked by pseudo-base stations. Furthermore, UNB needs to build its own network. Finally, the extremely low power consumption of the UNB terminal chip is mainly achieved by limiting transmitting capacity. For example, the life of a 2500 mAh lithium battery l could last for 10 years only if the system required to send 1 message per day. If it needed to send 140 messages per day, then the battery could last only about 2 months.

3.5 Summary

This chapter briefly presented the basic concepts of a few communication and networking technologies commonly applied in building agricultural IoT systems. It includes the basics of wired and wireless communications which lays the foundation for all communications and of course also to agricultural IoT systems as both wired and wireless means of communication are used at the same time in those system.

For building an agricultural IoT system, the network topological design could be the first challenge people need to address as it plays an essential role for getting the required coverage with suitable operating strategies for different applications. This chapter also provides the needed information for understanding those concepts.

As our society becomes more information-intensive, existing communication technology is constantly advancing, with new technologies being continuously invented, to provide users the increasing needs for more, faster, and easier access of information support anytime and anywhere. So, the technologies suitable for some applications as introduced here may be replaced by some more advanced technologies. Nevertheless, this chapter provides the readers the fundamental knowledge on understanding the basic principles of communication and networking technologies needed for building agricultural IoT systems.

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Chapter 4
Soil Information Sensing Technology

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Abstract Soil is what crops depend on for water, nutrients, and mineral elements; however, it sometimes suffers from severe pollution of heavy metals and pesticide residues, which significantly hinders crop growth and that in turn leads to losses in yield. It is therefore imperative to measure both the beneficial compositions (moisture and nutrients) and the detrimental compositions (heavy metals and pesticide residues) in soil to develop demand-specific approaches with respect to the irrigation, fertilization, and remediation of polluted soil. Traditional laboratory testing methods are time-consuming, labor-intensive, and hence not suitable for large-scale soil testing. In this field, the promising technology of rapid and non-destructive testing of soil information has been widely studied in recent years. To help you better understand soil information sensing technology, an introduction of relevant technologies and devices for measuring soil moisture, nutrients, heavy metal, and pesticide residues is laid out in this chapter.

Keywords Soil nutrient · Soil parameters · Spectral sensing technology · Spectral sensing devices

4.1 Introduction

Sustained growth of plants is achieved by drawing water and other elements from soil through the root system, which is why plant growth is subject to soil moisture, nutrients, and contamination levels. The traditional irrigation and fertilization methods tend to be extensive, in that it is believed doing more, resulting in the waste of resources and environmental pollution, is better than doing less, reducing crop yield and income. In addition, as industries rise globally and as urbanization advances,

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excessive amounts of urban sewage and industrial wastes have been discharged, most of which are imposed on soil, posing a major threat to agricultural production.

Modern agriculture, such as precision agriculture and smart agriculture, is guided by the concept of refined farming that is green, efficient, and eco-friendly. Modern agriculture incorporates demand-specific approaches of irrigation and fertilization, which can make full use of resources and minimize the impact on the agro-environment. Generally speaking, soil information includes water content, nitrogen, phosphorus, potassium, organic components, and pollutants such as heavy metals and agricultural residues. Though traditional laboratory testing methods allow for accurate detection of the abovementioned soil information, they are often accompanied with high costs, long testing periods, and poor real-time performance. Recent years saw extensive and worldwide research on rapid and non-destructive testing of soil information, and major progress was achieved.

To draw an overall picture of soil information sensing technology, this chapter covers an introduction of a number of sensing technologies, including detection technologies of soil moisture, nutrients, heavy metals, and pesticide residue, and the application of the corresponding devices.

4.2 Soil Information Sensing Technology

4.2.1 Soil Moisture Content Sensing

Soil moisture content is an indicator that is critically important and easy to detect relatively. The current international standard method for measuring soil moisture content is the classic oven drying method. The process of calculating the soil moisture content by this method is as follows: Collect a certain amount of soil sample and put it in an oven after weighing it. Then dry it at the temperature of 105~110 °C for 6~8 hours to the soil sample constant weight. Weigh and record the quality of the sample at last. The difference between the quality of the soil before and after drying is the mass of water in the sample soil. As it is determined by ratio of the mass of water to the mass of dry soil, it is also called the dry-base moisture content of the soil. The specific calculation method is as shown in Eq. (4.1). The method has reliable results, high accuracy, and low requirements on equipment, but it is time-consuming and laborious, and it cannot detect the soil moisture content online in a non-destructive manner in real time, which fails to meet the needs of fine agriculture.

$$\text{Moisture Content}\left(\%\right) = \frac{w_0 - w}{w} \times 100\% \tag{4.1}$$

where w_0 is the weight of the soil before drying (g) and w is the weight of the soil after drying (g).

In order to realize the rapid detection of soil moisture in the agricultural production process, scholars in related fields have tried a variety of moisture measurement methods, forming contemporary soil moisture measurement technology with distinctive characteristics. According to the measurement principle, the soil moisture detection technology can be divided into the following types:

- Time-domain reflectometer (TDR). Based on the principle of measuring the difference between the dielectric constant of water in the soil and other media, the time-domain reflectometer test technology is used to detect soil moisture. Its advantages are fast, convenient, and continuous observation of soil water content.
- Time-domain transmission (TDT). The characteristic of TDT technology is that the propagation of electromagnetic waves in the medium is one-way. It is only necessary to detect the signals transmitted in one direction of the electromagnetic waves and not necessary to obtain the reflected signals. This technique is based on the principle of difference of soil dielectric constant to determine soil moisture content.
- Frequency domain reflection (FDR). The basic principle of FDR is to form a capacitor between the electrode inserted in the soil and the soil (the soil is treated as a dielectric) and form a loop with the high-frequency oscillator. The characteristic of this technology is that the high-frequency signal is generated by a specially designed transmission probe, so that the impedance of the transmission line probe changes with the change of soil impedance.
- Neutron moisture probe. The neutron moisture probe consists of a high-energy radioactive neutron source and a thermal neutron detector. The neutron source emits fast neutron rays of energy ranging from 0.1 to 10.0 M electron volts in all directions. In soil, fast neutrons are quickly decelerated by the surrounding medium into slow neutrons, which are mainly affected by hydrogen atoms in the water, forming a slow neutron "cloud ball" with a density and moisture content around the detector scattered to the detector. Slow neutrons generate electrical pulses and are counted. The principle is that the number of slow neutrons counted in a given time is related to the volumetric water content of the soil. The larger the neutron count, the greater the soil water content.
- Tension meter. Measuring the tension in unsaturated soil is based on a principle similar to the way in which plant roots draw water from the soil. It has a parameter to measure: the force exerted by the crop to draw water from the soil.
- Resister method. Porous media block gypsum resistor block is usually used to measure soil moisture, but its sensitivity is low, and it is currently not widely used.
- Near-infrared spectroscopy. It uses the absorption of soil moisture in the near-infrared band to determine the soil moisture content.

4.2.2 Soil Nutrient Information Detection

The traditional chemical analysis method is to quantitatively analyze the content of a specific element in a soil sample by using a specific extraction solution. In the traditional chemical analysis method, the process of soil sample measurement, liquid addition, and extraction is the key to limit the speed of soil nutrient analysis. Researchers have made a number of improvements to these key steps and developed a series of specialized equipment to greatly increase the speed of soil nutrient analysis. For example, the soil sampler uses the volume method to take samples. Compared with the traditional weighing method, the sample measurement speed is increased. The special liquid adder and liquid adder increase the speed of quantitative solution addition and quantitative transfer, which can effectively reduce the errors in this process. The multiple soil sample mixer speeds up the process of soil nutrient extraction and reduces the errors of multiple soil sample confusion. Even so, because the process of chemical analysis of different elements with different extracts is too complicated, which greatly limits the processing capacity of soil nutrient analysis in the laboratory, researchers are actively exploring other alternative methods for fast detection of soil nutrients. The main detection methods are as follows.

4.2.2.1 Ring Paper Chromatography

Block et al. (2016) described a circular paper chromatography method (CPC method), the core principle of which is to separate the substances in the soil by using capillary tissue on a suitable filter paper. First, the filter paper is treated with a light-sensitive substance, and then the soil sample solution is dropped on the filter paper. The size, shape, and color of the diffusion pattern are used as data for measuring the nutrient content of the soil sample. Agronomists from India combined this technology with modern image processing technology to develop a fast and low-cost method for soil nutrient determination, which is called an alternative analysis method. This method first measures the nutrient data of a large number of soil samples by conventional methods and then collects the chromatograms of these samples by CPC method, forming a database by image processing software. The nutrient data of the same pattern within the error range is used as the nutrient data of the test sample after comparing the patterns of the samples to be tested with the patterns in the database to directly extract them.

4.2.2.2 Ion-Sensitive Field Effect Transistor Method

Ion-sensitive field effect transistor (ISFET) is a semiconductor component used to measure the concentration of metal ions in a solution. The working principle is that the interaction between the ions in the solution and the gate dielectric causes a change in the gate voltage. The concentration of a specific ionic substance in the electrolyte can be determined by measuring this voltage change. The ISFET method can effectively detect the pH value and the content and change of potassium, calcium, and nitrogen ions in soil, as well as the nitrogen content in soil in real time. The advantage of the detection method is that the ISFET method can quickly and accurately detect the nutrient element content in soil. However, there is no research on the effect of detecting medium and trace elements.

4.2.2.3 Plant Root Simulation

Qian and Schoenau (1996) studied the determination of nutrient isolates in soil by ion exchange resin membrane for three consecutive years, which is called plant root simulation (PRS) method. The researchers immersed the resin film in 0.5 mol·$L^{-1}NaHCO_3$ for 24 hours and buried it in the soil. After a predetermined time, the effective nutrients were resolved with 0.5 mol·L^{-1}HCl, and the effective N and P were determined by colorimetry. K was measured with a photometer, and S was measured with a plasma emission spectrometer. The study found that soil nutrients extracted with ion exchange resin membranes have a strong correlation with soil nutrients measured by traditional methods, which can better simulate plant nutrient absorption. This method can simplify the process of soil testing. The field embedding method can better reflect the actual distribution of soil nutrients as well. Its limitations are the lack of research on the applicability of other medium and trace elements and the difficulty of collecting samples due to the long burial time. At the same time, it still involves the laboratory treatment of the precipitated elements in the later stage, so it is difficult to apply to the development of soil nutrients speed tester.

4.2.2.4 Near-Infrared Spectroscopy

The chemical bond vibration of most organic and inorganic compounds will produce combined frequency and doubled absorption in the near-infrared spectral region. Near-infrared spectroscopy (NIRS) analysis technology uses the specific absorption of near-infrared light in a specific band by chemical molecular hydrogen-containing functional groups to obtain an absorption spectrum and then uses the chemometrics methods to analyze the data to qualitatively and quantitatively detect the component. The near-infrared spectroscopy of substances contains extremely informative molecular structure and state information. This technology has been applied to the analysis of soil nutritional components in recent years. The application of near-infrared analysis technology to soil nutrient analysis has many advantages: no pretreatment required, fast speed, and low cost. The test results are less disturbed by human factors. The spectrometer technology applicable to laboratories has matured in the 1990s, but generally has the disadvantages of large size, high price, and inconvenience in use. The handheld miniature spectrometer is of great significance for measuring soil and fertilizing. In recent years, with the development of microfabrication technique in the field of micro-optical electromechanical systems, binary optics, and integrated optics, the production of miniature spectrometers has been realized; especially the miniature spectrometers using dispersion systems have been put into practice.

4.2.3 Soil Heavy Metal Detection

Soil is one of the main natural resources on which human beings depend, and it is also an important part of human ecological environment. With the intensification of industrial, urban pollution, as well as the increase in the types and quantities of agricultural chemical substances, soil heavy metal pollution has become increasingly serious. According to the degree of toxicity of heavy metals in the soil, currently polluted elements that have attracted much attention include copper, lead, chromium, mercury, nickel, and cadmium. Excessive heavy metal content in the soil will directly lead to disturbances in the physiological system and development process of crops, resulting in a decline in yield and quality. For example, excessive heavy metal lead content will reduce the intensity of plant tissue oxidation, photosynthesis, and fat metabolism, hindering plant growth; excessive levels of heavy metal cadmium in the soil will damage the chlorophyll content in the leaves of crops and inhibit the moisture and nutrients in the soil at the roots of crops, while the lack of nutrients in crops leads to reduced yields. At the same time, soil heavy metals are absorbed and enriched by plants and animals and then accumulated into the human body through the food chain, which will seriously damage human health (Li 2014).

The commonly used traditional soil heavy metal detection methods include atomic fluorescence spectroscopy, atomic absorption spectroscopy, and plasma emission spectroscopy:

- Atomic fluorescence spectroscopy is between atomic emission spectroscopy and atomic absorption spectroscopy. It is a method for qualitative or quantitative analysis of substances by using the wavelength and intensity of atomic fluorescence lines. It can effectively determine trace arsenic, antimony, bismuth, mercury selenium, tellurium, germanium, and other elements in soil.
- Atomic absorption spectroscopy is a quantitative analysis method based on the absorption of the atomic resonance radiation, which is in the ground state, of the element under test in the vapor state. According to different detection purposes, it can be divided into flame atomic absorption spectroscopy and graphite furnace atomic absorption. The graphite furnace method, which can reach PPB level, has high detection accuracy. Its stability is slightly worse yet. Comparatively speaking, the detection on cadmium and lead in soil is more reliable. The flame method has a short detection time. A large number of metals can be measured by this method. The detection accuracy is not as good as that of the graphite furnace method, which is the PPM level.
- Plasma emission spectroscopy that is comprehensive has higher requirements on science and technology. Plasma emission spectroscopy can fully integrate various analysis methods and improve the efficiency and accuracy of soil heavy metal detection at the same time. During the detection process, the content of relevant elements in the sample can be determined by analyzing the intensity of the characteristic line. This analysis method is highly efficient. It has very convenient characteristics by effectively simplifying the operations of the relevant operators.

4.2.4 *Soil Pesticide Residue Detection*

Pesticide residue refers to the general term for all derivatives such as pesticide parents, impurities, metabolic transformation products, and reactants that directly or indirectly remain in organisms, agricultural products, aquatic products, and soil. There are many kinds of pesticides, with different the chemical structure composition and properties of pesticides. Due to the extremely complex soil matrix components and background, there are many interference impurities, which makes it difficult to detect soil pesticide residues. The detection of pesticide residues in soil is generally trace ($mg \cdot kg^{-1}$) and ultra-trace ($\mu g \cdot kg^{-1}$), which requires high-precision pesticide residue detection technology (Wang 2013). At present, the conventional methods for the detection of soil pesticide residues are mainly gas chromatography (GC), liquid chromatography (LC), gas chromatography-mass spectrometry (GC-MS), and liquid chromatography-mass spectrometry (LC-MS). These detection methods have the advantages of wide application range, high separation efficiency, good reproducibility, strong selectivity, multiple residue analysis, and accurate qualitative and quantitative analysis. However, these traditional methods usually need to rely on expensive large-scale instruments. Because of high cost, of long detection time, the time is long, and of tedious operation steps, it is difficult to achieve the purpose of fast real-time detection. In addition to the conventional detection methods, in recent years, there have been some new rapid detection methods with strong specificity and high sensitivity, such as enzyme inhibition, immunoassay, spectral detection, and biosensors.

4.2.4.1 Chromatography Method

Chromatography is most commonly used in the detection of soil pesticide residues. Chromatography mainly includes gas chromatography and liquid chromatography. Their basic principle is as follows: under the same conditions, different compounds have different physical and chemical characteristics, and the diffusion speed and partition coefficient on the chromatographic column are different to achieve the separation of the mixture. The difference is that the mobile phase of gas chromatography is an inert gas and the mobile phase of high-performance liquid chromatography is a liquid. Gas chromatography is generally suitable for the analysis of volatile and thermally stable compounds, while high-performance liquid chromatography has been improved on the basis of gas chromatography. At present, the detection sensitivity of ultra-performance liquid chromatography (UPLC) is two to three times higher than that of high-performance liquid chromatography. UPLC is currently being applied to pesticide residue analysis. Chromatography has the advantages of high sensitivity, low detection limit, and accurate and reliable results, which has led to develop into a mature method for pesticide residue detection.

4.2.4.2 Chromatography-Mass Spectrometry

Chromatography can separate and analyze complex mixtures, but there are certain difficulties in the qualitative identification of compounds. Mass spectrometry is an important method for qualitative identification and structural analysis, but it lacks the separation function. Therefore, using a chromatograph and a mass spectrometer in series can not only separate complex mixtures but also realize the identification of molecular structures, qualitative and quantitative analysis, and molecular weight determination of unknown compounds in the mixture. Chromatography-mass spectrometry has broad application prospects in soil pesticide residues. However, chromatographic-mass spectrometry also has shortcomings. Connecting chromatograph and mass spectrometer in series makes the instrument larger in size, detection cost higher, operation more complicated, and large-scale detection and portable real-time field detection difficult to achieve.

4.2.4.3 Multi-spectroscopy

Compared with chromatography and chromatography-mass spectrometry, spectroscopy has great potential for rapid detection of pesticide residues. Spectroscopy has the advantages of simple sample preparation, low destructiveness, and fast analysis speed. The detection of pesticide residues based on spectroscopy generally includes hyperspectral and imaging techniques, near-infrared spectroscopy, fluorescence spectroscopy, mid-infrared spectroscopy, ultraviolet spectrophotometry, and Raman spectroscopy. Zhang et al. (2011) used fluorescence spectroscopy to detect carbamate pesticides commonly used in fruits. Liu et al. (2018), Zhou et al. (2019), and Shan et al. (2020) detected organic carbon, total nitrogen, and atrazine sorption in soil based on visible-near-infrared detection techniques, respectively. The results of the experiment are satisfactory. Wang et al. (2017) used mid-infrared Fourier-transform spectroscopy to directly estimate soil heavy metal bioavailability.

4.3 Soil Information Sensing Devices

4.3.1 Types of Soil Sensors

Soil sensors are divided into invasive or non-invasive sensors by measurement methods. Depending on different principles, they can be divided into electrical and electromagnetic sensors, optical and radiation sensors, mechanical sensors, electrochemical sensors, etc. Both invasive and non-invasive sensors can be used to measure soil indexes that include moisture content, nutrient content, heavy metals, and pesticide residues. More specifically, compactness and pH values are measured by invasive sensors, while electrical conductivity and soil gas composition are mainly

Table 4.1 Test index and typical instruments of different types of soil sensors

Types of sensors	Index	Typical instruments[a]
Electrical and electromagnetic sensors	Texture, soil organic matter, salinity, water, etc.	Ground conductivity meter, Veris 3100, time-domain reflectometer (TDR), spectrum reflection instrument
Optical and radiometric sensors	Texture, soil organic matter, CEC, pH, water, salinity, soil temperature, soil roughness, mineral, pesticide residue, etc.	Spectrometer, ground-penetrating radar, laser-induced spectrum
Mechanical sensors	Compactness, drought resistance force, water, etc.	Pointer soil compactness meter
Electrochemical sensors	pH, nitrate, nutrient, etc.	pH meter, ion-sensitive transistor sensor

[a]*Disclaimer*: Commercial products are referred to solely for the purpose of clarification and should not be construed as being endorsed by the authors or the institution with which the authors are affiliated

measured by non-invasive sensors. Table 4.1 lists the index and typical instruments of different types of soil sensors.

4.3.1.1 Electrical and Electromagnetic Sensors

Electrical and electromagnetic sensors are used to measure the conductivity and capability of soil particles so as to accumulate charges by changing current. When the instrument approaches or invades the soil that awaits measurement, that soil becomes part of the electromagnetic system, and the voltage or the current will instantaneously change in line with the geographical positions. At present, this type of sensors is mainly used for the measurement and analysis of soil properties such as soil salinity, soil clay content, clay layer burial depth, soil nutrients, and soil moisture. Equipped with electromagnetic induction technology, these sensors are superior in terms of testing speed, real-time performance, costs, and so on. These sensors can be installed on agriculture-oriented vehicles, and when combined with Global Positioning System (GPS), they would enable fast scanning of soil conductivity. The information that the sensors capture, with the help of professional analysis software OASIS, geographic information system (GIS), and MATLAB, can be transformed into a three-dimensional information display of soil profile. However, measurement during field operation is also subject to a number of external factors, including temperature difference, moisture content, mineral components, and clay content. Thus, research on the corresponding compensation algorithms is essential for the elimination or reduction of interferences. For example, repeated zeroing calibrations of an instrument significantly reduces the impact of temperature difference on detection accuracy.

4.3.1.2 Optical and Radiometric Sensors

Optical and radiometric sensors are mainly used to measure soil characteristics by analyzing information of electromagnetic energy. Electromagnetic waves are generated by changes in the trajectory of electrons and electronic and nuclear transitions inside atoms. Atom-level electron movements of different substances differ, and so does the energy be required for electronic and nuclear transitions. Due to the correlation between the level of energy and the wavelength and frequency of optical waves, optical waves of different wavelengths produce different spectral characteristics. The primary wavelengths used in soil detection include visible light (Vis, 380~780 nm), near-infrared (NIR, 780~2500 nm), mid-infrared (MIR, 2500~25,000 nm), and terahertz (1 THz = 1012 Hz, 30 μm~3 mm), laser-induced breakdown spectroscopy (LIBS), and high-energy rays (such as X-rays and γ-rays). Depending on the required speed and accuracy of detection, either single-band or multi-band waves can be selected to detect soil moisture, nutrients, heavy metals, pesticide residues, and other pollutants.

4.3.1.3 Mechanical Sensors

As mechanical sensors push and pull in soil, the resistance forces, such as shearing, fracture, and filling, as well as the friction and adhesion resistance in the surface are sensed and recorded. Afterward, an analysis of the above parameters can produce estimated mechanical impedance of soil. During operation, the pressure generated by the sliding and cutting in soil with probes will be applied to the capacitor ring. This force will then be transferred to the pressure sensor through the pressure lever and be recorded. Based on the correlation between soil properties and impedance, models can be established to provide information on compactness, drought resistance, and moisture distribution.

4.3.1.4 Electrochemical Sensors

Though information of soil property can be acquired quickly and at low costs using electromagnetic induction sensors and resistance sensors, they fail to directly obtain status of soil nutrient concentrations. Electrochemical sensors, on the other hand, do provide key information of soil nutrient concentrations and pH value. The core idea of the "on-the-go" measurement mode is to install near-earth soil sensors on agriculture-used vehicles for the real-time measurement of relevant soil parameters. Near-earth sensors that feature fast scanning when moving are primarily electromagnetic and optical radiation instruments, such as EM38 earth conductivity meter, ground-penetrating radar, Vis/NIR, and γ-ray sensors. The multi-sensor integrated platform of information acquisition makes possible complementary and comprehensive use of information among sensors.

4.3.2 Soil Moisture Sensors

4.3.2.1 Capacitive Sensors

Thanks to the rapid development and wide application of integrated circuit technology, the 1970s saw the advent of sensors based on the principle of miniature capacitance measuring instruments and capacitance meter. The nature of capacitive sensors is to translate non-electricity into electric capacity so as to measure soil moisture. When soil is measured using these sensors, the detection scale (capacitance value) is directly correlated with the distance between the two plates of the capacitive sensor, the effective area between the plates, and the dielectric constant between the plates. If two of the parameters are constant, the corresponding capacitance value will change in line with the rest of the parameters. It is apparent that when changes in research parameters correlate, to a certain degree, with those in research objects, the latter's status can be reflected by changes in the former. Therefore, by changing the above parameters, one acquires capacitor plates with different shapes and structures and hence derives different capacitive sensors (Ma 2016).

Essentially the working process of capacitive sensors is to acquire different capacitance values by changing the dielectric between the capacitor plates. Capacitive sensors are usually calibrated by drying before use. The capacitance value obtained is positively related to the dielectric constant of the dielectric substance between the plates, and based on varying dielectric constants of different substances, soil moisture can be detected. The dielectric constant of dry soil is 2~5, and that of water is 81, hence dielectric constant will vary in step with change of the water content, and as a result, the capacitance value measured will also change, which allows for indirect measurement of moisture content. Capacitive sensors for measuring soil moisture are relatively mature, and they come with multiple functions and applications in the market. There are commercial products available for soil moisture sensors that can simultaneously detect soil moisture and temperature levels and auto-calibrate moisture readings according to temperature for achieving accurate soil moisture measurement. Some soil moisture sensors are equipped with Internet of Things functions. Such sensors can, through wireless communication, transfer the collected soil moisture information to the cloud, which keeps users informed of soil moisture status in real time for the implementation of precision irrigation.

4.3.2.2 Near-Infrared Sensors

Near-infrared moisture meters are based on the principle that water absorbs infrared radiation in specific infrared bands. When infrared radiation is reflected or transferred from the material, water content can be reflected via attenuation of the radiation. The theoretical basis for measuring soil moisture content by NIR reflectance is to monitor soil moisture using the characteristics of water absorption. Zhou et al.

(2019) developed a portable soil moisture sensor based on NIR reflectance spectroscopy and tested its performance, which demonstrated the feasibility of measuring soil moisture with near-infrared spectroscopy. The soil moisture content detection based on NIR is significantly affected by both soil quality and the "relief" effect caused by small changes in soil surface and the number of water seals in the gaps of soil surface. Christemen and Hummed of Purdue University attempted the application of NIR spectroscopy with different wavelengths to study soil samples. It was suggested that the difference in reflectance between 1880 and 2066 nm shares strong correlation with moisture content. Yin et al. (2013) developed a soil moisture sensor based on the water characteristics of strong absorption in the 1940 nm and weak absorption in the 1800 nm. The result indicated that under different soil conditions, a strong linear correlation exists between moisture and spectral absorption intensity, and the predicted moisture content agrees with that obtained using traditional air-drying method.

As a non-contact, rapid, and non-destructive way to detect soil moisture, spectroscopic technique is also easily affected by the roughness and water-filled gaps of soil surface. In addition, it is difficult for light to penetrate soil; thus, the technique can only measure surface moisture content. Excavation is necessary if measurement of moisture content in deep soil is required.

4.3.2.3 Tensiometer Sensors

Tensiometer sensors are widely used for moisture measurement in certain soils. This instrument, which comes with a porous porcelain head that is connected to a vacuum gauge through a water-filled tube, is inserted into soil. The porous porcelain head is closely attached to the soil, and the vacuum gauge is set on the ground.

Research on tensiometer sensors started fairly early, starting with Gardner et al. (1922), who adopted tensiometer to measure the tension of unsaturated soil water for the measurement of water content. Later on, Richards (1949) modified the instrument and adjusted it for production and laboratory research, and Richards was followed by Mekin, who replaced water with ethyl alcohol absolute as the solution to study the application of tensiometers in cold regions in 1976 (Feng 2005). Tensiometer incorporates a relatively simple structure and principle. Using the instrument, soil can be measured in real time, and the flow direction and penetration depth of water can be determined, yet it comes with equally prominent shortcomings. For instance, the instrument responds slowly, which means that the time required to equilibrate before reading is long. Furthermore, its narrow measurement range is fetal when it comes to extremely dry soil. When used for the long term, the pipe of the instrument needs replenishment with water if it is hot dry season. In addition, their fragile porcelain head requires relatively costly regular maintenance or even replacement.

4.3.2.4 Time-Domain Reflectometry Sensors

Time-domain reflection (TDR) represents a high-speed measurement technology of dielectric measurement. It was developed based on studies of the dielectric properties of various liquids, and it was originally used to locate defects in communication cables. The basis for TDR measurement is the physical phenomenon that the speed at which electromagnetic waves travel changes in dielectrics with different dielectric constants. Soil moisture, for instance, has major impact on soil dielectric properties. In external electric fields, the degree of polarization in water is far outstrip than that in other substances. Moreover, in the microwave band, the dielectric constants of water differ under different wavelengths. The dielectric constant of water is significantly larger than that of air, and that of moisture holds a dominant position in the soil matrix. The components of TDR soil moisture sensor's detection part include a pulse generator, the coaxial transmission line, a probe, and a high-frequency oscilloscope. Upon completed detection, the result will be transmitted to the display terminal through the data port, as shown in Fig. 4.1. It should be noted that the application scope of TDR sensor is quite limited owing to its high cost and complexity of operation.

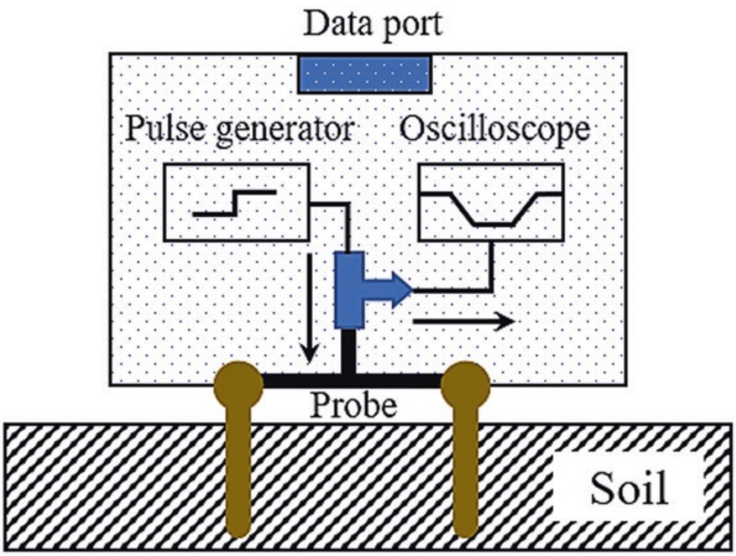

Fig. 4.1 Working principle of TDR soil sensor

4.3.3 Soil Nutrient Sensors

4.3.3.1 Portable Detectors

Using portable soil detector, accurate point data of soil can be obtained, and when the instrument is adopted in combination with the interpolation analysis method, one obtains the distribution of nutrients or mineral elements on plane scale. Such combination is now widely used in small-scaled production. It is noteworthy that soil organic matter is the most common index detected by portable detectors. Sudduth and Hummel (1993) firstly designed a portable near-infrared spectrophotometer in 1993 to detect organic matters on the surface of soil. The critical component of this instrument is a circular variable filter monochromator, which generates near-infrared light in the range of 1650–2600 nm and an optical bandwidth under 55 mm by rotating the driving motor. Spectrophotometers designed in such a manner achieve relatively high accuracy and also facilitate development of similar equipment in the future. Li et al. (2010) designed a portable detector that can be used to detect the content of organic matter in the underground soil, with a maximum detection depth of 30 cm (Fig. 4.2). Using an 850 nm near-infrared LED lamphouse as the light source, the instrument relies on the Y-type optical fiber to transfer optical signals. Its probe is inserted into soil to create a confined space, while the light from the light source, transferred to the top of the probe via the incident fibers, illuminates the soil located around the top. The diffused reflection light from the soil is transferred to the photoelectric conversion device via fibers, and the generated current is sent to the circuit unit for amplification, filtering, A/D conversion, display,

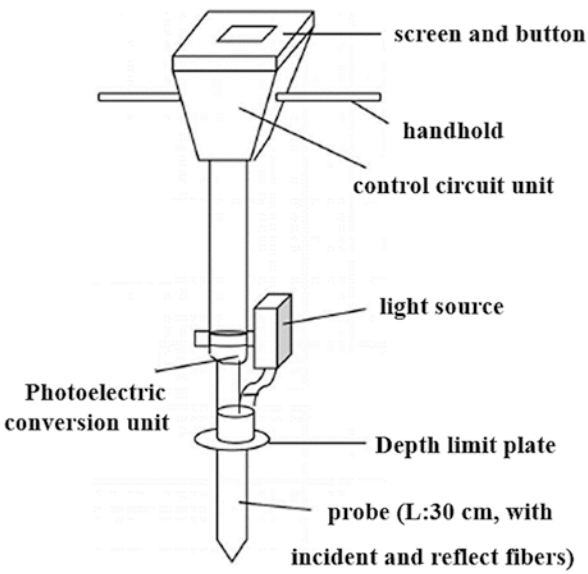

Fig. 4.2 Sketch map of the portable soil organic matter detector

Table 4.2 Parameters of portable apparatus

Parameter	Indexes
Weight	1.9 kg
Size	Length, 240 mm; width, 163 mm; height, 144 mm
Wavelength	345~1042 nm
Response time	1 s
Hard disk	Solid-state disk
Input voltage	12 V
Built-in model	Soil organic matter and total nitrogen, 5 s to switch
USB interface	2 external USB
Data transfer speed	4 ms (USB2.0)
Screen	Touch screen

and storage. With regard to natural soil samples (moisture content of about 20%), the coefficient of correlation between the detected soil organic matter content and the measured reflectance is 0.950, and as for dried soil samples, the correlation coefficient is 0.982, indicating that the detector is practical, and hence meets production needs.

Based on spectroscopic technology, the research team led by Professor Yong He at Zhejiang University created a portable soil total nitrogen content detector (refer to Table 4.2 for the relevant parameters) (He 2016). The detector features a system equipped with multiple functional modules that comes with sufficient content and reasonable structure. One can choose keyboard and mouse or touch screen to operate the detector for data collection. When spectra are acquired, data can be immediately displayed on screen, which enables convenient inquiry. The software that is embedded into the detector adopts a structured and modular design concept, decomposing operations into independent functional modules. Additionally, the software is reasonably structured and it allows visualized operations. Compared with the chemical approach, the accuracy of this detector is higher and its deviation smaller. Refer to Fig. 4.3 for the flowchart of the main program.

4.3.3.2 Vehicular Detectors

Compared with portable soil detector, vehicular detectors are more efficient at sampling and less laborious in terms of operation. By installing soil sensor at the back of the trencher, soil information can be obtained as the trencher ditches the groove, thus achieving real-time sampling. Adopting such an approach, one can detect soil information while ditching and obtain fertility information on an ongoing basis, and in comparison with fixed-point sampling, more comprehensive soil information can be obtained.

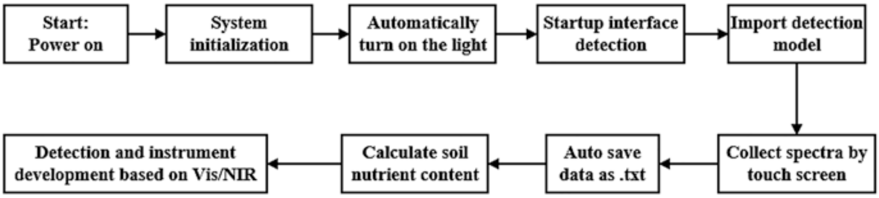

Fig. 4.3 Flowchart of the main program for total nitrogen detection

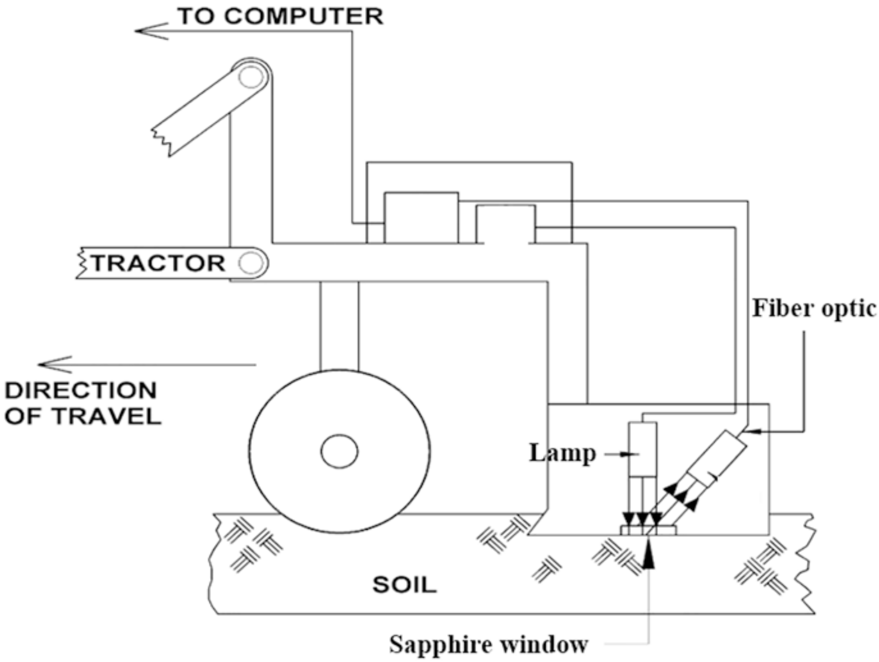

Fig. 4.4 The shank-based spectrophotometer used to obtain NIR reflectance spectra

Christy (2008) developed a device for real-time detection of soil properties relying on visible-near-infrared spectroscopy (Fig. 4.4). When the detector works, the sensor is illuminated by a tungsten halogen bulb, and its observation plane is approximately 7 cm lower than the ground. Moreover, the machine advances at a speed of roughly 6 km/h, collecting 20 soil spectra per second. Spectrophotometers with the key components have a spectral range of 920~1718 nm and a spectral resolution of 6.35 nm. During field test, the determination coefficient of the prediction model is 0.67, and the root mean square error is 0.52%. The test results show that vehicular detectors are suitable for online measurement of the spatial variation distribution of organic matters in soil.

Based on the above research, Veris Technologies developed a corresponding soil property detector, which uses visible and near-infrared spectroscopy to obtain soil spectrum with specific locations and calculates the contents of soil organic matter, carbon, pH, soil moisture, and phosphorus through the established soil-spectral relationship model. Such detectors consist of a spectral sensor, a trencher, a controller, and data acquisition software. The adjustable depth of the trencher is 3.8~10.2 cm. After the smooth and firm surface of the furrow is ditched, reflection spectrum of soil is detected through the measurement window, which is free of dust interference and can be automatically cleaned, at the bottom. The detector is an integration of two spectrometers, with a spectral band range of 450~2200 nm, a spectral resolution of 8 nm, and a detection speed of 20 spectral data per second. Soil nutrient content can be quickly obtained via analysis using controller.

The Allis-Gleaner Corporation created a real-time vehicular sensor by the name of Smart Firmer (Fig. 4.5), which is suitable for precise variable seeding. The sensor is directly installed at the rear of the seeding trencher, and no additional trencher for soil nutrient detection is required. A three-band spectral detection unit is attached to the side of the sensor, so that soil information on the side of the sowing groove can be quickly detected. The sensor measures soil moisture, temperature, crop residue, and organic content and produces a real-time sowing prescription map to guide variable sowing. Additionally, this sensor also enables real-time seeding of prescription variables, saving one the trouble of making prescription maps compared to the seeding of prescription pattern variables.

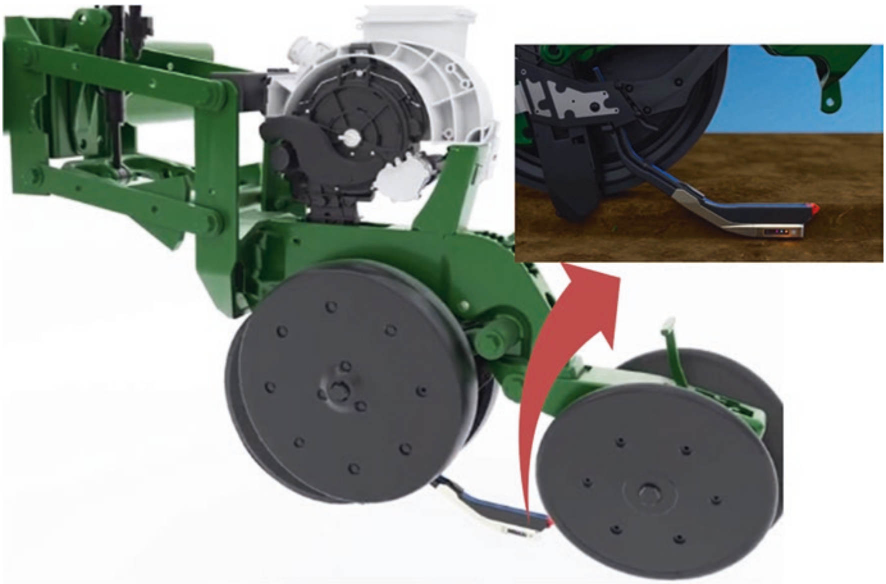

Fig. 4.5 The real-time soil sensor Smart Firmer developed by Allis-Gleaner Corporation

4.3.4 Soil Heavy Metal Sensors

As a promising technology of analysis and measurement, LIBS boasts excellent performance in metal element detection, which complements general spectral techniques' failure to detect metal elements. LIBS technology analyzes multiple elements at the same time and achieves fast and on-site detection and analysis under truly non-contact conditions. Moreover, whether the detection object is solid, liquid, or gas, this kind of sensor is pollution-free. In a nutshell, the advantages of LIBS can be concluded as continuous detection and fast analysis.

Back in the 1990s, scientists pioneered a series of studies on applying LIBS to soil heavy metal detection. As early as 1994, scientists at the International Association for Remote Sensing Science announced that they had successfully detected As, Cd, Cr, Hg, Pb, Zn, and other metal elements in soil using LIBS technology. In 1996, Los Alamos National Laboratory in the United States pioneered the development of the portable soil metal detector named TRACER. The time required for measurement and analysis is less than 1 min, and the maximum measurement depth can reach 60.95 cm. Yu et al. (2016) adopted laser-induced breakdown spectroscopy in combination with chemometrics for the quantitative analysis of lead (Pb) and cadmium (Cd) in soil. According to the different degrees of heavy metal pollution, LIBS spectra were collected from soil samples containing ten concentration gradients of Pb and Cd elements. Based on the peak information of Pb and Cd elements in the LIBS emission line and the standard atomic spectrum database of the National Institute of Standards and Technology (NIST), lines and intervals of the Pb and Cd analysis were selected. Furthermore, linear regression and partial least squares regression analysis algorithm were applied to establish a quantitative regression model between the spectral line interval and the corresponding Pb and Cd concentrations. The predicted correlation coefficient of PLSR model for Pb is 0.9485, and the root mean square error is 2.044 mg·g^{-1} (Fig. 4.6a); the predicted correlation coefficient of PLSR model for Cd is 0.9949, and the predicted

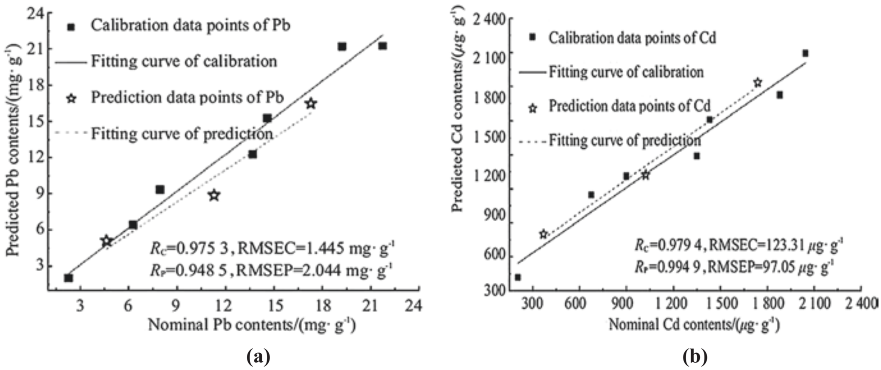

Fig. 4.6 Calibration and prediction results of PLSR model. (**a**) Calibration and prediction results of PLSR model for Pb. (**b**) Calibration and prediction results of PLSR model for Cd

root mean square error is 97.05 ug·g^{-1} (Fig. 4.6b). The result turns out that LIBS has a high detection accuracy.

At present, there are a number of portable LIBS soil detectors on the market, such as the EasyLIBS portable laser spectroscopic element analyzer, which can be used for online detection of the constant elements N, P, K, Ca, Mg, and S and the trace elements Fe, Cu, Mn, Zn, B, Mo, Ni, and Cl in soil. It determines the focal position of each laser through the intersection of the probes by built-in dual laser probes, thereby improving the accuracy of the focal position and the accuracy of repeated tests.

In this regard, terahertz spectroscopy also stands out as a potential candidate for detecting metals in soil. Li and Zhao (2016), for instance, explored the mechanism and feasibility of using terahertz time-domain spectroscopy to detect lead content in heavy metals in farmland soils. They used Z-2 terahertz time-domain spectrometer to collect terahertz transmission spectrum data of dry soil samples and preprocess the spectral data, including smoothing, multiple scattering correction, and baseline correction. The least squares method and genetic algorithm-partial least squares method were adopted to establish a calibration model of lead content in soil samples and predict the lead content in the prediction set. As a result, it was demonstrated that performance is at its best when using the feature band selection based on genetic algorithm combined with partial least squares method. The correlation coefficients of the calibration set and prediction set are 0.86 and 0.81, respectively, while the error and the predicted root mean square error were 23.55 mg·Kg^{-1} and 39.52 mg·Kg^{-1}, respectively.

4.3.5 Soil Pesticide Residue Sensor

Soil pollution has now manifested itself as a serious problem – food safety and sustainable agriculture are threatened by excessive levels of pesticides and heavy metals in soil. Against this backdrop, the detection and treatment of soil pollution have become an increasingly urgent task. Organophosphorus and urethane pesticide residues in soil can already be detested quickly and accurately with existing detectors. The principle of such detection is that organophosphorus and carbamate pesticides inhibit the normal function of cholinesterase, and the inhibition rate is positively related to the concentration of pesticides. Under normal circumstances, the enzyme catalyzes the hydrolysis of nerve conduction metabolites (acetylcholine), and the hydrolysate developer then reacts to produce a yellow substance. The detection instrument of pesticide absorbance is used to measure the change in absorbance with time and to calculate the inhibition rate. Thus, judging by the inhibition rate, it would be clear whether the sample contains organophosphorus or urethane pesticides. The error rate of this approach is 3~10%, and the lower detection limit is 0.3~3.5 mg·kg^{-1}.

Focused on the rapid detection method of soil pesticide residues based on surface-enhanced Raman spectroscopy, Dong (2019) achieved the qualitative

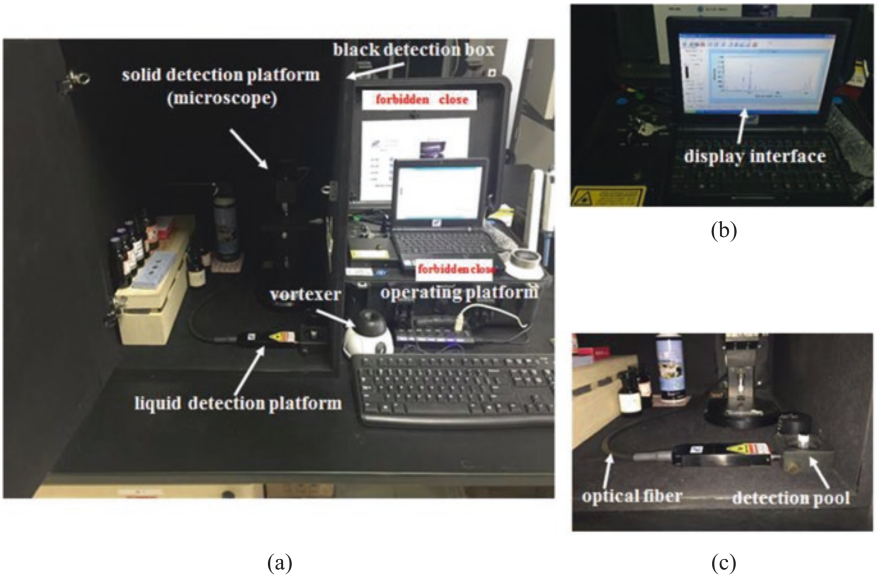

Fig. 4.7 An example of Raman instrument detection platform. (**a**) The whole views of detection platform. (**b**) Display interface. (**c**) Liquid detection platform

identification and quantitative detection of three common and highly toxic pesticides, including chlorpyrifos, deltamethrin, and carbofuran. Dong's research provided theoretical foundation and technical support for research on the detection and control of pesticide residues in soil. The study involved the use of a SERS substrate suitable for the detection of soil pesticide residue. Furthermore, the relationship between the size of gold nanoparticles and the SERS signal was investigated, and the detection limits of three different pesticide residues were increased using the SERS substrate, with the minimum detection limit kept at 0.025 mg·kg^{-1}. The portable Raman spectrometer used in the experiment was RamTracer-200-HS (Optus Technology Co., Ltd.), as shown in Fig. 4.7. This instrument taps into a diode-stabilized frequency exciter with an excitation wavelength of 785 nm, a spectral acquisition range of 200~3200 cm^{-1}, a resolution of less than 2~4 cm^{-1}, and a maximum laser power of 400 mW.

4.4 Summary

Visible-near-infrared spectroscopy yields sound prediction accuracy in analyzing soil moisture content, organic matter content, nitrogen content, phosphorus content, some mineral component content, and physical and chemical characteristics. Portable or vehicular real-time analyzer of farmland soil spectrum, once developed, would play a major role in the popularization of soil detection, formula seeding, and fertilization technologies, which would, in turn, promote the application and development of precision agriculture.

Modern spectral analysis methods such as LIBS spectrum analysis technology and THz spectrum technology demonstrated outstanding capabilities in soil composition and characteristic parameter detection, particularly in soil heavy metal content detection. These methods are quite promising for application. Raman spectroscopy has presented us with advantages in the detection of soil pesticide residues. Basic research on soil detection based on LIBS, THz, and Raman spectroscopy and revelation of the absorption characteristic parameters of these spectroscopy techniques under different soil types and soil composition conditions should remain as our future task. In addition, low-cost LIBS, THz, and Raman spectrometers, to be developed based on the characteristics of soil analysis, would make agriculture significantly more information-based and sustainable, and they would also enable the adoption of more fine agriculture.

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Chapter 5
Crop Information Sensing Technology

Fei Liu, Yong He, Qin Zhang, Wei Wang, and Tingting Shen

Abstract Precision agricultural practice requires getting aware of crop growth situation via sensitive, accurate, economical, and fast sensing means to improve decision-making for production management. Supported by IoT technology, big data analysis, and digital detection, crop information sensing technologies have been advanced rapidly. Though the traditional chemical detection instruments could meet the requirement on the accuracy and sensitivity, these methods do present disadvantages like complicated procedures, high costs, and long detection time. For overcoming these disadvantages, extensive research has been undertaken to develop technologies for detecting crop growth information via spectral methods. This chapter introduces the academic progress in developing spectral sensing technologies for detecting crop nutrient, phonological and phonemic awareness, diseases, and content of heavy metal and pesticide residue, including near-infrared reflectance spectroscopy, hyperspectral imaging, laser-induced breakdown spectroscopy, terahertz technology, and surface-enhanced Raman spectroscopy.

Keywords Spectral sensing · Crop nutrient sensing · Morphologic sensing · Disease detection · Heavy metal detection · Pesticide residue detection

5.1 Introduction

Crop information detection is critical for dynamic monitoring and precise management in crop production and a core sensing technology for agricultural IoT. Traditionally, the detection of crop information uses chemical means, such as gas chromatography (GC), high-performance liquid chromatography (HPLC), gas

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chromatography-mass spectrometer (GC-MS), and liquid chromatograph-mass spectrometer (LC-MS). These chemical detection methods could provide superior accuracy and sensitivity, yet the requirement for preliminary treatment of samples is quite demanding, often involving complicated processes, high costs, and long detection time. They are categorized as destructive detection and are not suitable for online use, i.e., to be connected to an IoT system. To address such disadvantages of traditional methods, extensive research has been undertaken in developing spectral-based digital detection technologies for acquiring crop growth information.

Spectroscopic sensing techniques allow automated non-destructive detection of plant disease and have become a future trend. The techniques have already been adopted for stress detection and quality detection of harvested crops (Sankaran et al. 2010). The spectral characteristics of crops are produced via interactions between crop growth and environmental factors. Thanks to the rapid development of information detection technology and instrument, spectral detection technology has been used extensively in crop information detection, including infrared spectroscopy, hyperspectral technology, laser-induced breakdown spectroscopy, terahertz technology, and Raman spectroscopy. Other than the richest information of crops under physiological stress (Sankaran et al. 2010), visible and near-infrared spectra also provides detection of leaf scales, pigments, and chlorophyll (Gandolfo et al. 2016) and crop diagnosis (Liu et al. 2010).

5.1.1 Near-Infrared Reflectance Spectroscopy

Near-infrared reflectance spectroscopy (NIRS) is an electromagnetic radiation wave between visible light (VIS) and mid-infrared (MIR). Defined by the American Society for Material Testing (ASTM), the near-infrared spectral band is 780~2526 nm, the first non-visible region in the absorption spectrum. Based on atomic electronic transitions and vibrational transitions, near-infrared spectroscopy senses the absorption, reflection, transmission, and/or scattering of light in or through the sample material, following the Lambert-Beer law. These transitions share the characteristics of overtones and combined modes (Kademi et al. 2019). Such detection could obtain qualitative and/or quantitative information from the interaction of near-infrared light with its components. In terms of near-infrared spectral region and hydrogen groups in organic molecules (O-H, N-H, C-H) of vibration frequency and the frequency doubling absorption area at all levels, the hydrogen characteristic information can be obtained by scanning the sample to detect its organic molecules in the near-infrared spectra. Furthermore, the adoption of near-infrared spectroscopy analysis is fast, efficient, accurate, economical, and non-destructive. This approach consumes no chemical reagents and brings zero pollution. As such, near-infrared spectroscopy drew huge attention in the academic community and evolved into an increasingly popular method for crop sensing and is mainly used to analyze protein, moisture, oil content, cellulose, and other nutritional component products in agriculture applications.

5.1.2 Hyperspectral Imaging Technology

As it could carry spectral information on each pixel, hyperspectral imaging technology could detect the chemical compositions and physical structures of the diseased area in terms of reflecting characteristics on plant leaves. A distribution map is often used to present such spectral information of each pixel, each spectral region features unique plant information, visible light provides information of leaf composition, and infrared band provides information of physiological indicators (Sankaran et al. 2010). Figure 5.1 illustrates the operational principle of a hyperspectral imaging system (Kong et al. 2013). Adopting hyperspectral imaging to classify diseased pear jujubes, Wang et al. (2013) applied LS-SVM to different spectrum ranges and achieved the highest average recognition rate of 99.12%. Tian et al. (2010) used hyperspectral imaging to detect cucumber diseases and found it could outperform other methods. Kong et al. (2018) found that using hyperspectral imaging for disease detection on the stem of oilseed rape could achieve a highest *Sclerotinia sclerotiorum* classification accuracy over 90%.

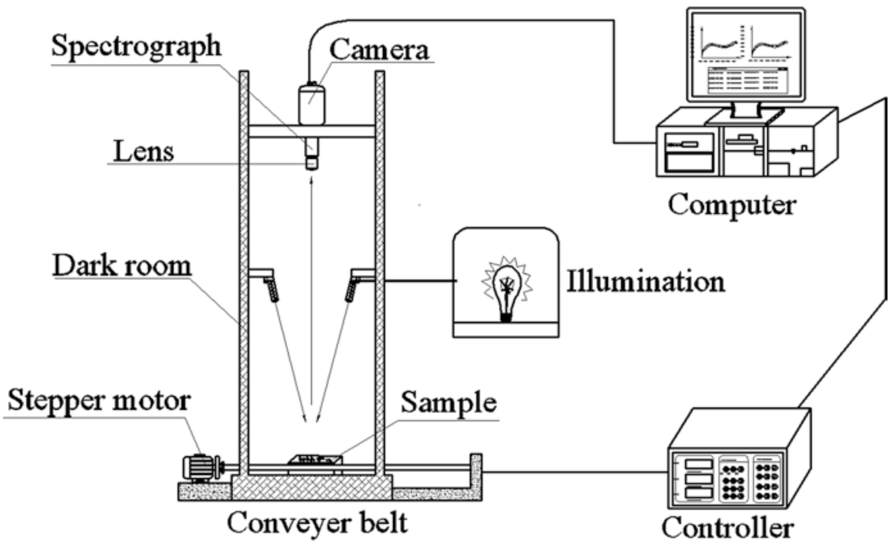

Fig. 5.1 Hyperspectral imaging system

5.1.3 Laser-Induced Breakdown Spectroscopy

Laser-induced breakdown spectroscopy (LIBS), an atomic emission sensing technique proposed by Brech in 1962 (Baudelet and Smith 2013), enables multi-element analysis based on the light emission from laser plasma. The technology boasts a few well-known advantages, such as fast analytical speed, multi-element analysis, minimal sample preparation, and high efficiency (Cremers and Chinni 2009). LIBS could support simultaneous analysis of multiple elements, with almost unlimited application, including solid objects, liquid, gas, or insoluble substances with high hardness (Peng et al. 2016, 2017, 2018). The nutritional elements of plants determine their resistance and susceptibility to diseases, which would inhibit the absorption and flow of nutrients (Tripathi et al. 2014). LIBS could also support continuous monitoring and real-time online analysis. When the remote analysis of optical fiber transmission is adopted, LIBS can transmit the laser beam and collect the plasma emission spectrum formed at the same time with the appropriate optical fiber system, thus making remote analysis possible (Kaiser et al. 2007). In conjunction with this matter, LIBS also can be combined with optical microscope or other chemical technology to improve its analysis and detection capacity and broaden its application scope. In the past few decades, LIBS has been applied in geochemical, environmental, biological, and archaeological analysis due to the abovementioned superiority (Cremers and Radziemski 2013). Several reviews have been published, covering the applications and progress of LIBS technique, which saw significant improvements on both detection performance and understanding of the mechanisms (Mueller et al. 2007). LIBS detection of geochemical and environmental materials (Harmon et al. 2013), industrial materials (Zhang et al. 2012), and biomedical application (Rehse et al. 2012) also gained certain academic focus.

Typical experimental platform of laser-induced spectrum breakdown is composed of laser generator, spectrum information acquisition system (spectrometer and detector), digital pulse delay generator, and accessories (El Haddad et al. 2014). Figure 5.2 illustrates the major components of a LIBS instrument (Shen et al. 2018). When a laser beam is first excited by the laser generator, it will pass through an optical path system to reach the surface of the sample. After ablating the sample, a plasma will be generated and spread outward in the form of energy radiation. The light collection system catches the optical signal and transmits it to the spectrometer and ICCD and then converts it into an electrical signal to be recorded. The qualitative and quantitative analysis of the elements in the sample is done by collecting and analyzing the wavelength and intensity information of the atomic or ion spectrum in the plasma. During the entire process of information acquisition and analysis, no sample pretreatment is needed for this non-destructive or almost non-destructive detection.

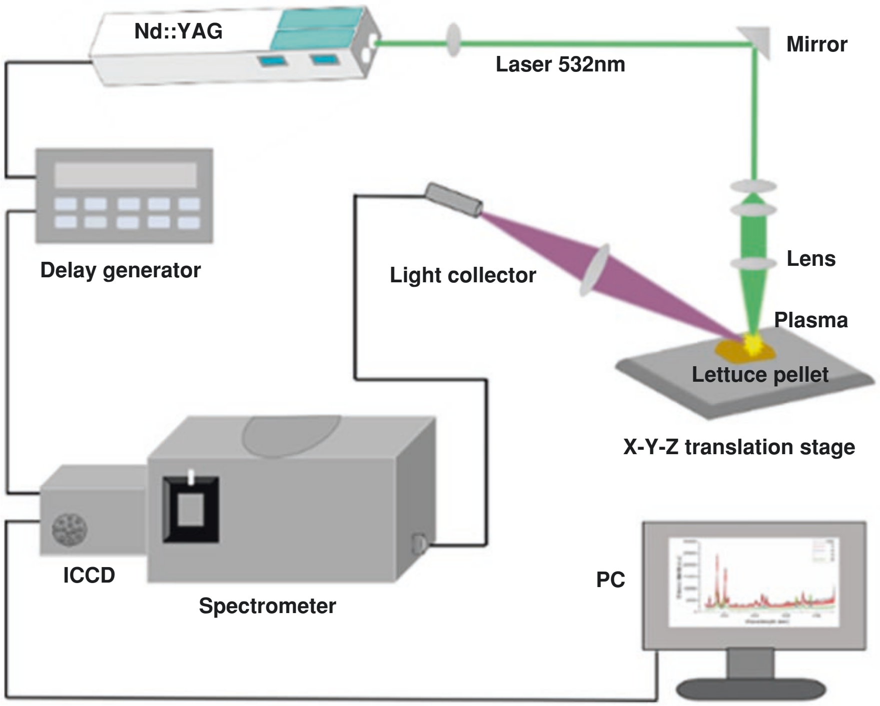

Fig. 5.2 Schematic diagram of the laser-induced breakdown spectroscopy (LIBS) experimental setup

5.1.4 Terahertz Technology

The absorption of heterogeneous and biological macromolecules differs in terahertz (THz) band. In general, the vibration absorption frequencies of many chemical bonds in organic molecules are mainly concentrated in an infrared band, except for weak interactions among molecules, such as dipole rotation, hydrogen bonds, van der Waals force, and vibrational transition, whereas low-frequency vibration absorption of lattices occurs mainly in THz band (Siegel 2004).

THz radiation features a few excellent functions that include fingerprint absorption, penetration, coherence, low ionization damage, and transients. Using ultra-short pulsed lasers, THz has improved its capability to identify a wide variety of materials and to determine the optical properties of many dielectrics and nonmetallic materials. The vibrational frequencies of intermolecular interactions, skeleton vibrations, oscillations, and the rotational transitions are located at the THz band (0.1~10 THz). In addition, materials with different chemical compositions or crystal structures react differently to THz in terms of absorption and dispersion. Therefore, THz radiation characterizes the unique spectral information of materials and enriches the spectral characteristics that other spectra cannot obtain (Qu et al. 2018a). This is particularly useful for the analysis of materials that requires accurate identification and testing.

5.1.5 Surface-Enhanced Raman Technique

The Raman technique is based on the principle that the signals in the compounds of molecules increase when rough metals are absorbed by the surface of the tested material, such as gold, silver, and copper (Farquharson et al. 2008). SERS (surface-enhanced Raman spectroscopy) also features simple pretreatment, convenient operation, and fast detection speed, which makes it suitable for rapid screening of complex compounds. Figure 4.7 shows a detection platform of Raman instrument, consisting of a portable Raman spectrometer, an electronic balance, a low-speed centrifuge, a vortex mixer, an Ultra-Performance Liquid Chromatography Combined Photodiode Array Detector, a column, a transmission electron microscope, and an intelligent thermostat magnetic stirrer. This Raman detection platform enables both solid and liquid sample detection.

5.2 Crop Nutrient and Physiological Information Detection

Supported by IoT, big data, and modern sensing technologies, many rapid crop growth information detection systems have been developed and applied in agriculture production. One effective method is the use of some types of crop indices to assess the growth status and the yield.

Crop nutrient information, such as nitrogen, phosphorus, potassium, and zinc, can tightly correlate with its growth status, and lack of any one element may cause abnormal growth of the plant. As important vegetative organs for photosynthesis, transpiration, and the flow of nutrients, leaves are generally composed of pigments, water, and various organic components. The adoption of precision agriculture often requires fast detection of such information, and one common practice is using spectroscopy and imaging sensing technology to detect crop nutrient and physiological information in a near-real-time and non-destructive manner. This approach can also be used to indirectly predict crop yield.

5.2.1 The Detection of Malondialdehyde

Leaf changes are indicators of plant growth and development as these changes reflect growth status of the crops. The decrease of assimilation function in leaves caused by senescence or premature senescence of crops could affect the yield. Therefore, it is of great importance to study the physiological information in crop leaves.

Membrane lipid peroxide refers to the biological membrane unsaturated fatty acids in free radical induced under the peroxidation of membrane peroxidation, and it separates the membrane phases and destroys the normal function of membrane. As one of the membranous peroxide products produced by the plant organ when plants aged or encountered abnormalities, malondialdehyde (MDA) can be toxic to plant cells. MDA content is generally used as indicators of the degree of membrane lipid peroxidation, reflecting the degree to which plants suffer from harms. The higher the MDA content, the more severe the peroxidation. It is thus a major indicator in physiological studies.

One method for dynamic monitoring of malondialdehyde online is the use of spectrum and imaging technology. Kong et al. (2011) used near-infrared spectroscopy supported by analytical tools based on least squares and support vector machine methods to achieve rapid detection of MDA content in oilseed rape leaves. They found an optimal LV-LS-SVM prediction model could an achieve satisfactory prediction accuracy with correlation coefficient $r = 0.9999$ and root mean square error of prediction (RMSEP) = 0.3957. This method provides a fast and accurate method for detecting leaf senescence and stress characterization during the growth of rape. Kong et al. (2012) have also applied visible/near-infrared spectroscopy technology for the rapid and non-destructive detection of MDA content in barley leaves and also achieved satisfactory results.

5.2.2 The Detection of Soluble Protein Content

The change of soluble protein content in plants represents one of the major indicators in plant stress physiology. As key components of plant enzymes, soluble proteins will take part in various plant physiological and biochemical metabolic processes, and its content will be changed when the plant under an environment stress. Kong (2015) used hyperspectral imaging technique to detecting herbicide residue stress in rapeseed plant non-destructively through determining the content of soluble protein in its leaves. A partial least squares (PLS) model was established for quantifying the soluble protein content in leaves in terms of the measured leaf reflectivity at 316 selected wavelengths within a 500–900 nm band. This model could accurately predict soluble protein content change, reaching $R_P = 0.931$ and RMSEP = 0.247.

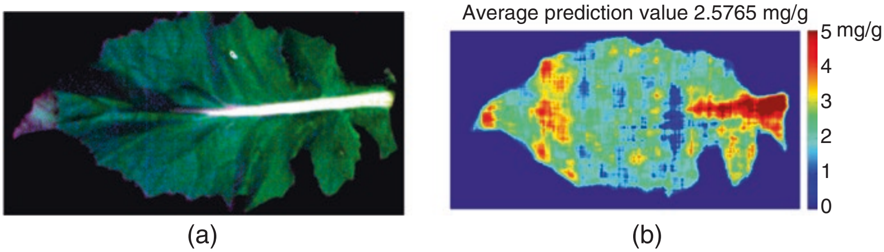

Fig. 5.3 The visualization map of predicted soluble proteins of oilseed rape leaf. (**a**) Original RGB image (**b**) and the distribution maps

Zhang et al. (2015) further improved the method by using visible and near-infrared hyperspectral imaging to detect the soluble protein content in oilseed rape leaves. They used a successive projections algorithm-partial least squares (SPA-PLS) model to establish a calibration model for the spectral and soluble protein content of oilseed rape samples at 500~900 nm and obtained r_{cv} and RMSECV values of 0.934 and 0.178 $mg \cdot g^{-1}$, respectively, proving that hyperspectral imaging can be efficiently used to estimate the soluble protein content of rape leaves. Figure 5.3 shows a visualization map of predicted soluble proteins obtained from the method developed by this research group, indicating this method could estimate the soluble protein content of rapeseed leaves accurately and precisely.

5.2.3 The Detection of Pigment Content

Environment stress is the general term for various environmental factors that are unfavorable for plant growth and development. Visible changes occur in the external morphological structure of plants under adverse conditions as well as in the external appearance, including rolling leaf, deciduous leaf, wilting, etc. Such appearance changes could lead to changes in plant canopy morphology. Meanwhile, many physiological and biochemical processes in the cell, such as the decrease of green quantity and photosynthesis or the decline of nutrient absorption and transportation, could be changed even before the appearance changes. As the contents of lutein, chlorophyll, carotene, and other pigments in leaf often share a close correlation with the photosynthetic rate and the nutritional status of crops, data of the abovementioned contents are essential for rapid diagnosis and accurate prediction of crop yield. In the actual monitoring of crop pigment content, spectral and imaging technologies based on direct spectral data or vegetation index can quickly and effectively predict the pigment content of crop.

The measurement of the pigment content and distribution on leaf reflects, to a certain degree, crop growth and various stresses. He et al. (2015) determined the pigment concentration of oilseed rape leaf using hyperspectral images with the data extracted from 500 to 900 nm and used the obtained data to build PLS, least squares-support vector machine (LS-SVM), and extreme learning machine (ELM) models for building calibration models to determine the concentrations of chlorophyll a (Chl a), chlorophyll b (Chl b), total chlorophyll (tChl), and carotenoids (Car). The LS-SVM model could perform relatively well only when the residual prediction deviation (RPD) value was higher than 2.0. The ELM model could yield the best prediction result with r_p of 0.929, RMSEP of 0.096 mg·g^{-1}, and RPD of 2.37. Similar results were obtained for Chl b regarding the estimation of calibration model concentration. The PLS model yielded the least satisfying result with r_p of 0.883, RMSEP of 0.046 mg·g^{-1}, and RPD of 2.01. With respect to the total chlorophyll concentration, the ELM model demonstrated an excellent performance with r_p of 0.912, RMSEP of 0.142 mg·g^{-1}, and RPD of 2.29. As for carotenoid concentration estimation, LS-SVM's performance ranked bottom, with the lowest r_p and RPD and highest RMSEP, whereas ELM ranked top.

Based on chlorophyll fluorescence imaging, Zhao (2016) acquired a fitting formula of chlorophyll content in oilseed rape leaf for hyperspectral imaging. Different types of stress, such as pests and plant nitrogen deficiency, could cause disorder of chlorophyll which often appears a varying distribution of chlorophyll on a leaf. Hence, using the chlorophyll distribution of tonal alone cannot directly determine the occurrence of plant disease, while fast preliminary judgment of stresses in plants can be achieved by looking at the distribution characteristics of leaf chlorophyll. By the same token, the results obtained by Yeturu et al. (2016) showed that the Raman peak at 1526 cm^{-1} stands out as ideal for the early detection of plant diseases. However, the types of disease cannot be determined relying on the variation of carotenoid content alone, as there are many reasons for the variation of carotenoid content in plants, including environmental factors and abiotic stress.

Zhang et al. (2017) adopted hyperspectral imaging to determine the pigment content of spinach leaf in the range of 874~1734 nm. The PLS model yielded acceptable results for all sample sets whose correlation prediction coefficients (r_p) were close to or above 0.8. The PLS model for selecting the best wavelength by random frog from the combined sample set performed well, with r_p of 0.813 and RMSEP of 0.235 for Chl a, r_p of 0.814 and RMSEP of 0.071 for Chl b, and r_p of 0.844 and RMSEP of 0.312 for tChl. The pixel spectrum is smoothed by Daubechies 4 wavelet transform and decomposed into three levels. Refer to Fig. 5.4 for the distributions of Chl a, Chl b, tChl, and Car. These prediction maps illustrate that most of the pixels were predicted to be within the corresponding concentration range, indicating the feasibility of visualization using hyperspectral imaging.

In conclusion, the application of spectral and imaging techniques for the analysis and monitoring of the nutrient and physiological information of crops is quite

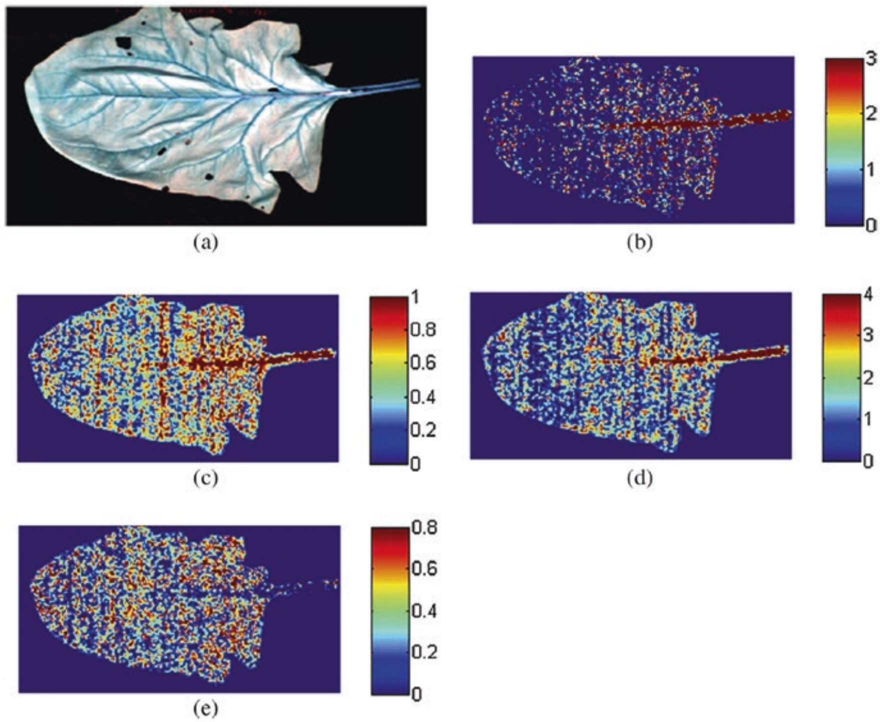

Fig. 5.4 The visualization map by applying the corresponding PLS models using optimal wavelengths on a randomly selected image. (**a**) Raw image and (**b**) prediction maps of Chl a, (**c**) Chl b, (**d**) tChl, and (**e**) Car

promising, and it may lead to improved production. The technology can be an important means to detect whether crops are under stress, and it also offers essential theoretical and technical basis for remote sensing monitoring and automatic farmland management.

5.3 Crop Morphology Detection

5.3.1 The Detection of Root Morphology

The root system is often the first organ in a plant to experience stress (Wijewardana et al. 2018), but it is very difficult to directly observe root morphological parameters and root microstructure without special instruments (Lade et al. 2018). In order to detect root morphological parameters, some root system analysis systems, integrating capable scanning systems with special graphic analysis software, are required for extracting selected parameters from scanned root system images. For example,

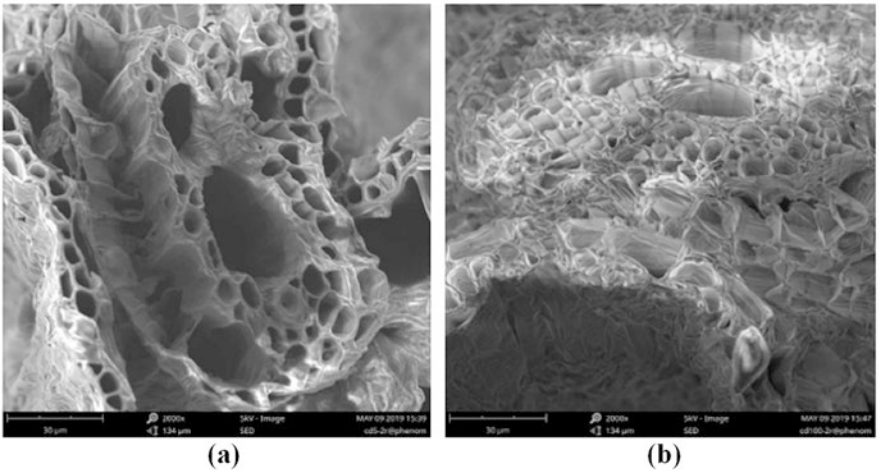

Fig. 5.5 Electron micrograph of rice root in (**a**) 5 μm and (**b**) 100 μm scales

one of such systems commonly used in related researches is the WinRHIZO root analysis system[1] (Pornaro et al. 2017; Marques et al. 2019). In recent years, a new method of combining scanning electron microscope technology and X-ray energy spectrometer (EDS) has been developed for its advantages of fast detection speed, high analytical sensitivity, and qualitative and quantitative analysis (Shen et al. 2016).

To observe the microstructure of plant root systems, Lin (2019) used a scanning electron microscope (SEM) to obtain the cross-section images of rice root. As shown in Fig. 5.5 (with a magnification of 2000 and a scale of 30 $\mu m \cdot cm^{-1}$), the obtained electron micrograph image could clearly show the differences of rice roots with a stress concentration gradient of 5 μm and 100 μm.

5.3.2 The Simulation of Maize Leaves

Nitrogen fertilizer plays a major role in the growth of maize organs. Chlorophyll, presenting a correlation with nitrogen status, is a "sensitive meter" for measuring nitrogen stress. Under nitrogen stress, the growth rate of stems and leaves of maize would slow down, the plant size and leaf area could become smaller, and the dry matter accumulation could be lower. Zhang (2015) designed a bidirectional reflectance distribution function (BRDF) platform for analyzing optical characteristics in maize leaf using MATLAB GUI interface. Through this platform, two-way reflection distribution function maps of maize leaf in different wave bands, different

[1] *Disclaimer*: Commercial products are referred to solely for the purpose of clarification and should not be construed as being endorsed by the authors or the institution with which the authors are affiliated.

orientations, and different nitrogen stresses could be graphically presented, and an anisotropy index (ANIX) could be used to reveal the leaf hemisphere reflection.

5.3.2.1 The Distribution of Different Bands

The bidirectional reflection characteristics can be used to detect the growing status of maize leaves. Normally, three bands were often used, including 550 nm (Green-VIS), 680 nm (Red-VIS), and 800 nm (NIR). As shown in Fig. 5.6, the maximum bidirectional reflectance distribution of maize leaves at 800 nm was larger than that at 550 nm and 680 nm, and the coverage was also wider, while the distribution of

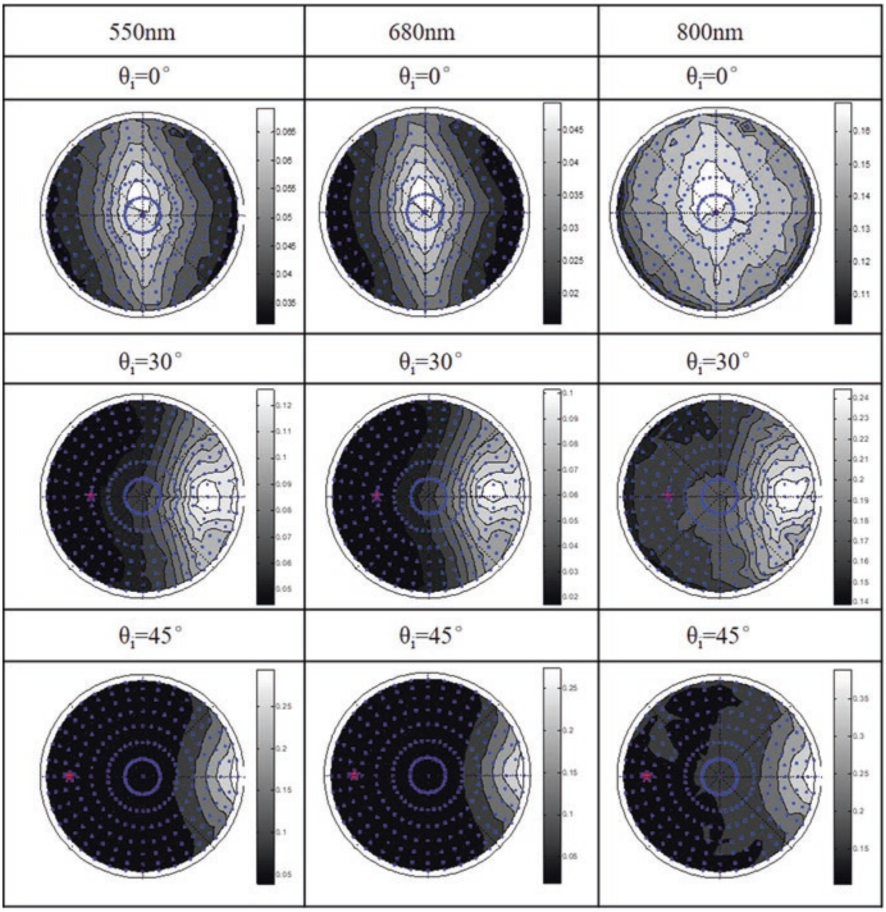

Fig. 5.6 Bidirectional reflection distribution of maize leaves at 550 nm, 680 nm, and 800 nm when the azimuth angle of the light source is $\phi_i = 180°$ and zenith angle $\theta_i = 0°$, 30°, and 45°. The blue point was the receiving probe rotation position, and the red pentagram was the light source zenith angle

maize leaves at 680 nm was less susceptible to systematic errors. Given that maize leaves are monocotyledons with parallel veins on the surface, when the light source parallel to the vein was incident, the blade roughness angle received by the detector was perpendicular to the principal plane direction; hence, the maximum value was mainly concentrated in the mirror direction. As the incident angle increases, the ANIX values in different bands coincided with such changes, which was driven by the presence of specular effects and forward scattering effects.

5.3.2.2 The Distribution of Different Nitrogen Stresses

BRDF could be used to reflect the chlorophyll values in different plant growing stages. According to relevant literatures (Biliouris et al. 2007; Combes et al. 2007), a single band of 680 nm was selected to compare the change of bidirectional reflection distribution function of maize leaves under different chlorophyll values. As can be seen from Fig. 5.7, the maximum value of f_r (the ratio of the infinitesimal quantity of reflected amplitude to the surface irradiance in a specific direction of the sample surface) decreased with the increase of chlorophyll concentration, while the minimum value showed little difference. This was mainly due to the incidence along the direction of the parallel veins of the leaves. When the chlorophyll concentration was lower, the specular reflection was stronger, the f_r value was larger, and the coverage area was larger. When the light source was incident at a certain angle, considering the mirror effect evaluated by the anisotropic factor (ANIX), the variation in the near-infrared band was close, yet a significant difference exists between the red and green bands of visible light. It was noticed that it is ideal to study nitrogen stress in maize when $\theta_i = 45°$.

5.3.2.3 The Characteristic of Different Parts

BRDF could reflect the optical properties of plant leaves at different positions. The early stage of the experiment determined that the same maize leaf had different SPAD values at different positions. Refer to Fig. 5.8 for the bidirectional reflection distribution of the maize leaf of the 550 nm and 800 nm bands at the position of the light source (45°, 180°). The maximum values of f_r at the leaf top, middle, and tip of the maize leaf were 0.391, 0.383, and 0.385, respectively, and the minimum values were 0.042, 0.047, and 0.045. The optical properties of the leaf top and tip position were not significantly different. The chlorophyll values were 35.8 $\mu g \cdot cm^{-2}$ and 36.9 $\mu g \cdot cm^{-2}$, respectively, which were close to each other. The leaf chlorophyll value was 40.8 $\mu g \cdot cm^{-2}$, and its ANIX showed the smallest wave peak in the red light range.

In conclusion, the BRDF platform could be used to analyze optical characteristics of maize leaves to quantitatively estimate the relationship between the optical characteristics of maize leaves and biomass.

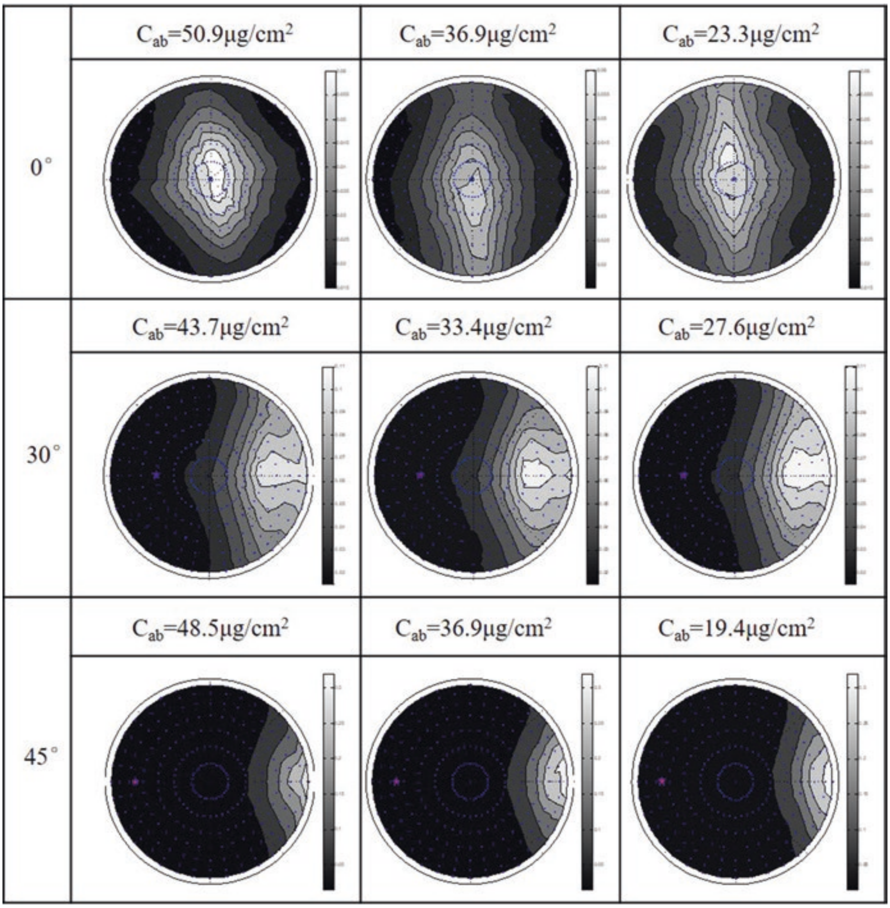

Fig. 5.7 Bidirectional reflection distribution characteristics of maize leaves under different nitrogen stress at 680 nm. C_{ab} is chlorophyll concentration value

5.4 Crop Disease Detection

5.4.1 Hyperspectral Imaging Technology for Crop Disease Detection

Hyperspectral imaging technology can obtain spectral and image information at the same time, and such information has been combined with chemometric method to detect the disease infection of crops. For example, Zhao et al. (2016) selected rapeseed petals as objects to detect *Sclerotinia sclerotiorum* in rapeseed by hyperspectral method. They used a one-way analysis of variance (ANOVA) to identify optimal wavebands for clearly reflecting the disease of petals and found that the leaf image taken at 1146 nm could achieve the best contrast for threshold segmentation to

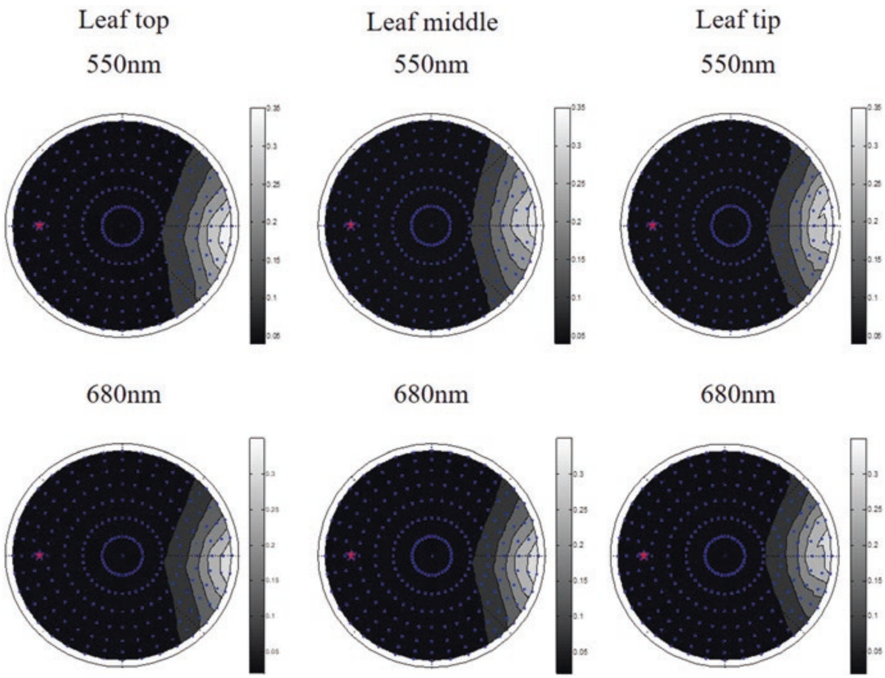

Fig. 5.8 The bidirectional reflection distribution characteristics at different positions of the same maize leaf under the light source angle of (45°, 180°)

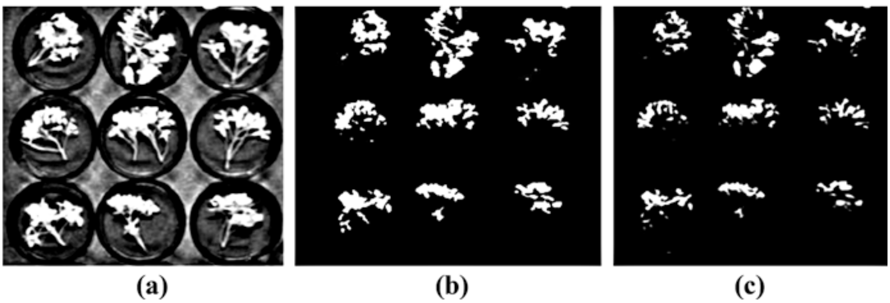

Fig. 5.9 Procedure of image segmentation for subsequent extracting spectral reflectance: (**a**) a gray scale image at 1146 nm, (**b**) petal mask, and (**c**) petal hyperspectral images without background

separate the disease-infected areas on the leaves (Fig. 5.9). Two methods including X-loadings of PCA and random frog (RF) algorithm were used to select the optimal wavebands. Full spectral range and optimal waveband were used as inputs for least squares-support vector machine (LS-SVM) model. The LS-SVM model using RF and X-loading selected wavebands achieved recognition rate of 92.68%, but 97.48% variables were eliminated in the optimal waveband selection process. The best LS-SVM model was using full spectral range with recognition rate of 100%.

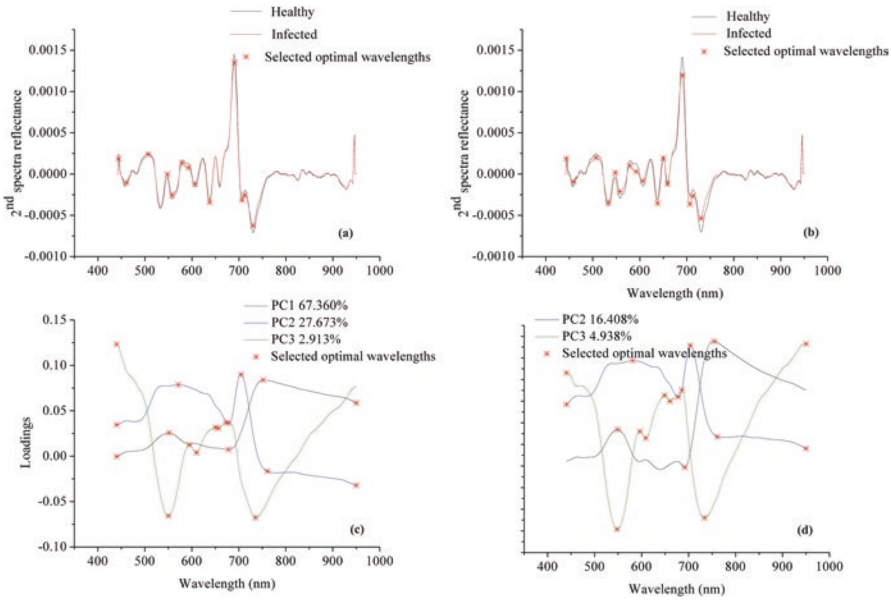

Fig. 5.10 Optimal wavelength selection and PCA loadings. (**a**) Optimal wavelength selection of sample set 1 by second derivative spectra, (**b**) optimal wavelength selection of sample set 2 by second derivative spectra, (**c**) the PCA loading set 1, and (**d**) the PCA loading set 2

Kong et al. (2018) reported the use of spectral sensor (384–1034 nm) to detect the infection of *Sclerotinia sclerotiorum* on rapeseed plants (*Brassica napus* L., cv. ZS758). They discovered significant differences according to the average spectra and pixel-wise spectra of stems, especially in the higher range of spectrum. To process the collected spectral data, they also established four models using partial least squares-discriminate analysis (PLS-DA), radial basis function neural networks (RBFNN), extreme learning machine (ELM), and support vector machine (SVM). The classification accuracies of the calibration and prediction set are equal to or higher than 87.5%. The ELM models performed best among all discriminant models with accuracy of 99.77% for calibration set and 99.50% for prediction set. Principal component analysis (PCA) loadings and a second derivative spectra were used as optimal wavelength selection methods (refer to Fig. 5.10 for the results). The RBFNN model could achieve an accuracy of 100% for calibration set and 97.50% for prediction set and therefore was the best model among the four tested models.

Another example was that Weng et al. (2018) combined the image information taken using a CCD camera with 672 × 512 pixels and the spectral information obtained using a spectrograph with a spectral band ranging from 379 to 1023 nm to detect tree leaves being infected by HLB disease. The cycle threshold (Ct) values of the control were higher than 30, which was defined as the threshold of differentiating HLB-infected leaves from the healthy and Fe-deficient ones. The optimal

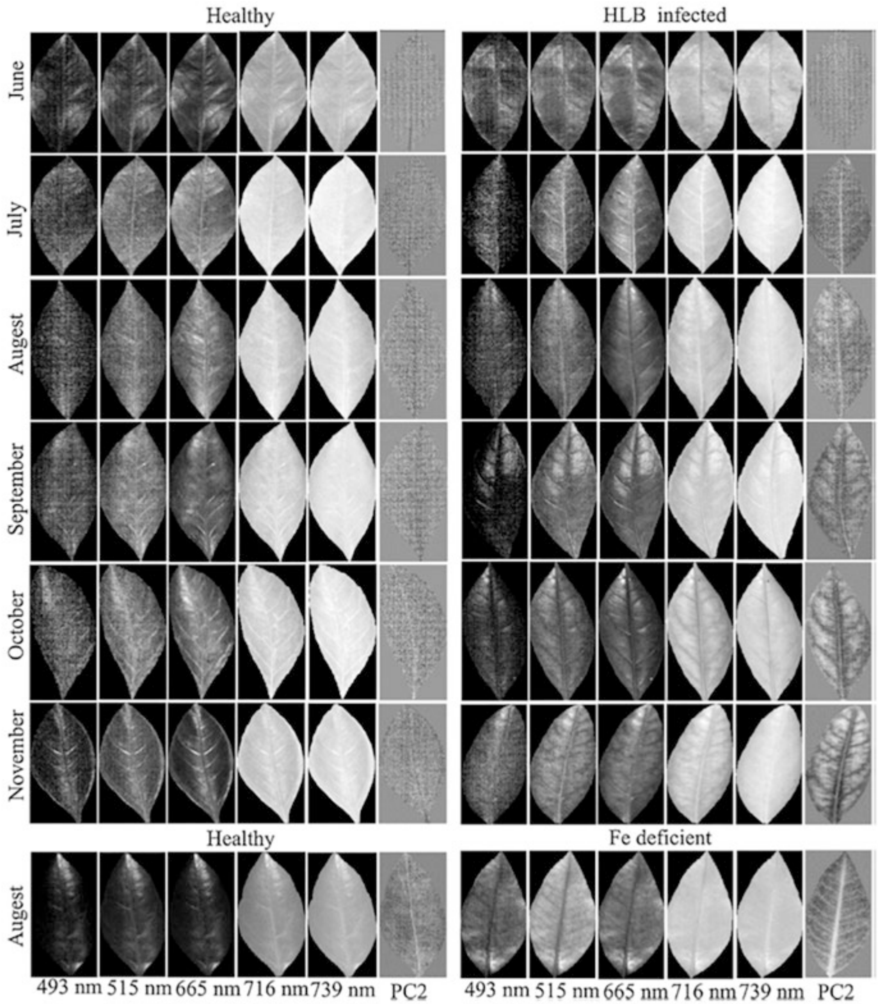

Fig. 5.11 Spectral images at selected wavelengths and the second principal component (PC2) images of healthy and HLB-infected leaves in 6 months as well as healthy and Fe-deficient leaves in August

wavelengths were selected by successive projections algorithm (SPA) from different seasonal sample datasets. Spectral images at selected wavelengths and the second principal component (PC2) images of healthy, HLB infected and Fe deficient leaves were shown in Fig. 5.11. Spectral and textural features from optimal wavelengths and principal component images were well linked to the HLB fingerprint. The least squares-support vector machine (LS-SVM) model was applied and obtained the classification accuracy of 93.5%.

5.4.2 LIBS Technology for Crop Disease Detection

Laser-induced breakdown spectroscopy (LIBS) technology can also be used to detect crop diseases, rapidly and non-destructively. Peng et al. (2017) have successfully utilized LIBS in detecting tobacco mosaic virus and utilized a partial least squares-discrimination analysis (PLS-DA) to examine the separability of full spectrum with full-cross validation strategy for dried and fresh leaf samples. As shown in Fig. 5.12, the classification performance of PLS-DA based on dried samples were higher than that based on fresh samples, with the accuracy of 97.2% in the prediction set.

Liu et al. (2018b) tried to use a custom-assembled LIBS system to distinguish healthy and *Sclerotinia* stem rot (SSR)-infected leaves of rapeseed plants. As shown in Fig. 5.13a, there existed some distinguishable difference on the average spectra from healthy and SSR-infected leaves. After preprocessing, the intensity of the spectra could be ramped up significantly as shown in Fig. 5.13b. A PCA process could be used to extract the significant differences between healthy and SSR-infected leaf samples. However, overlaps still lingered, which is why further steps are required for sample discrimination. The second derivative was applied to the average spectra of healthy and SSR-infected leaves, and 24 emission lines were

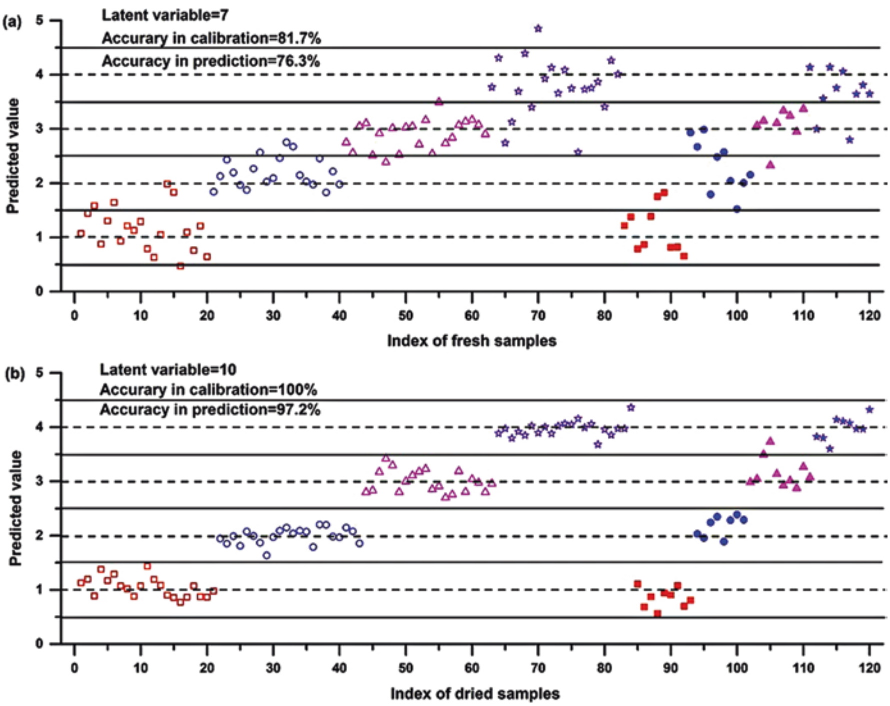

Fig. 5.12 Y-predicted plot for PLS-DA classification of different symptoms of infected plants based on full spectrum of (**a**) fresh samples and (**b**) dried samples

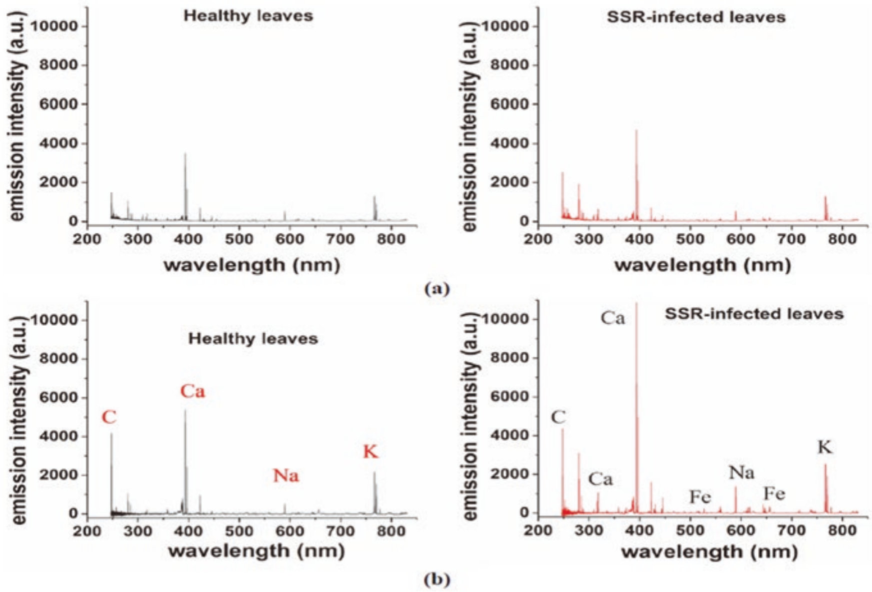

Fig. 5.13 Healthy leaf and *Sclerotinia* stem rot-infected leaf based on LIBS. (**a**) Average of 50 LIBS spectra for one healthy leaf and one SSR-infected leaf and (**b**) corresponding average spectra preprocessed by robust baseline estimation and wavelet transform

selected as optimal wavelengths. Further studies showed that the variables corresponding to the 24 emission lines were taken as input vectors to establish K-nearest neighbor (KNN), radial basis function neural network (RBFNN), random forest (RF), and extreme learning machine (ELM) models to classify healthy and SSR-infected samples. The prediction accuracy of the RBFNN model based on 24 emission lines was 75%. The ELM classification model achieved the best results, and the accuracy was 91% and 85% for calibration and prediction set, respectively. The results indicated that LIBS was feasible to detect SSR on oilseed rape leaves.

5.4.3 Thermal Infrared Spectroscopy for Crop Disease Detection

Here are some other methods based on spectroscopy to detect crop disease. Cao et al. (2018) investigated a method of analyzing the maximum temperature difference on a single leaf thermal images and tracking the temperature change in infected area over a 5-day period to detect rapeseed plants infected with *Sclerotinia sclerotiorum* and found that the maximum temperature difference (MTD) on rapeseed leaves was significantly higher, reaching the maximum level the second day after

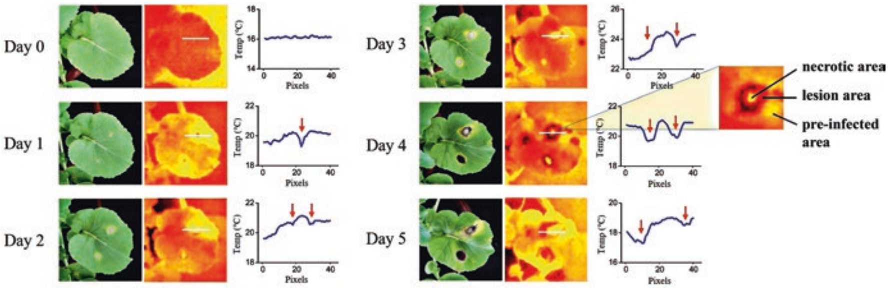

Fig. 5.14 The temperature change curves through the lesion area before and after infection. (**a**) Day 0–day 2 and (**b**) day 3–day 5

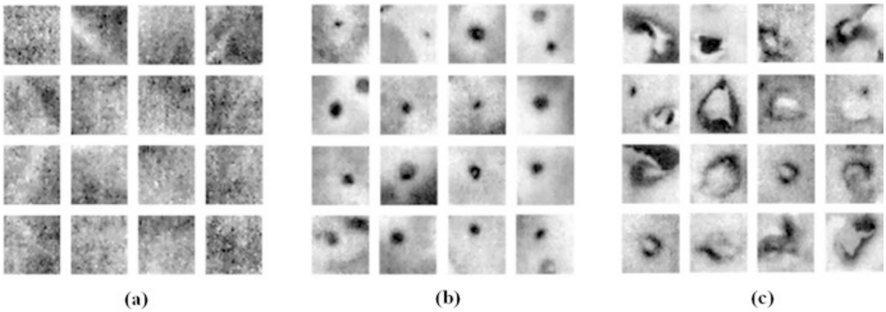

Fig. 5.15 Three disease severity levels. (**a**) Level 0 for healthy samples, (**b**) level 1 for mild infected samples, and (**c**) level 2 for severe infection samples

being infected. Figure 5.14 illustrates the temperature change curves that represent the temperature variation of white lines on thermal pseudo-color images.

The author selected a 32 × 32 pixels area from the leaf sample of oilseed rape as data sample, shown in Fig. 5.15. It is noteworthy that a certain relationship exists between the degree of infection and number of infected days. Day 0 represents healthy samples (level 0), day 1 represents mild infected samples (level 1), and day 5 represents severe infected samples (level 2). Min-max normalization was then adopted to process the 32 × 32 pixels area, and a 240 × 1024 vector was built as the thermal dataset. Four machine learning models were established using thermal images and fused images, respectively, including support vector machine (SVM), random forest (RF), K-nearest neighbor (KNN), and naïve Bayes (NB), and SVM model obtained a classification accuracy of 90.0% on the task of classifying disease severity (Cao et al. 2018).

Zhang et al. (2017) explored the capacity of oilseed rape leaf infection detection using mid-infrared spectroscopy. They tried to use wavelet transform (WT) to reduce the noises in mid-infrared spectra, which constituted an efficient approach in relation to spectral analysis. The most significant difference occurred in the range of 900–1500 cm^{-1} for sample set 1 and 1800–2750 cm^{-1} for sample set 2. The first

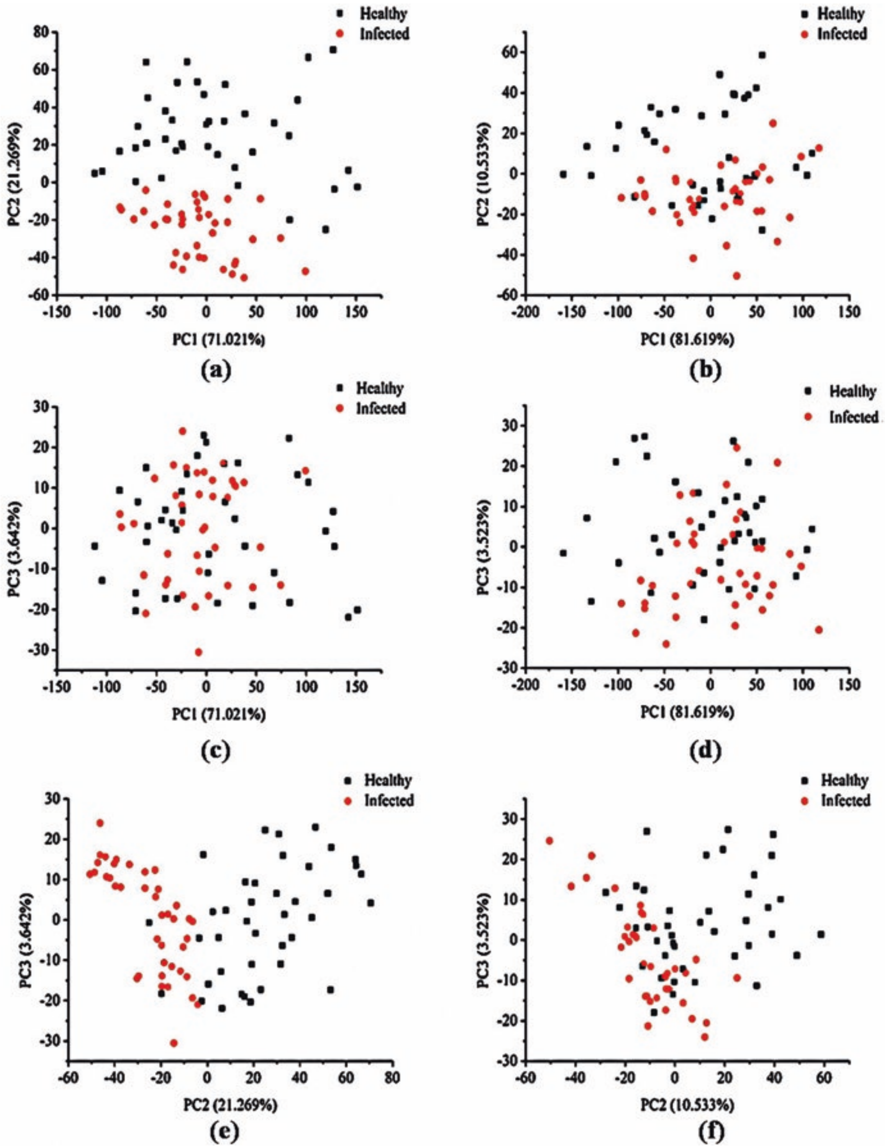

Fig. 5.16 Scores of scatter plot of sample set 1: (**a**) PC1 versus PC2, (**c**) PC1 versus PC3, and (**e**) PC2 versus PC3. Scores of scatter plot of set 2: (**b**) PC1 versus PC2, (**d**) PC1 versus PC3, and (**f**) PC2 versus PC3

three principal components (PCs) offered explanation for the 95.931% and 95.675% of the total variance for sample set 1 and sample set 2. As illustrated in Fig. 5.16, the healthy samples and infected samples can be separated with a few overlaps, and the distribution of healthy samples disperse more widely, and the result concluded that sample set 1 and 2 can be classified using PCA. Among three PLS-DA, SVM, and ELM models building to use the full mid-infrared spectra of the sample sets in classifying healthy and infected leaves, the PLS-DA model showed the best results, with classification accuracies of 100% in the calibration and prediction sets.

5.5 Crop Heavy Metal Detection

One of the major problems in agriculture is the contamination of toxic heavy metals. Toxic heavy metals, such as the metalloids arsenic (As), selenium (Se), cadmium (Cd), lead (Pb), chromium (Cr), and mercury (Hg), bind to sulfur-, nitrogen-, and oxygen-containing functional groups in the molecules of crops, including structural proteins, enzymes, and nucleic acids (Clemens 2006). Toxic metals, if critical levels are exceeded, disturb the normal functioning of the functional molecules in crops. Furthermore, chronic exposure to toxic metals may cause severe health problems to humans and animals through the food chain. The proper control of nutrients is one of the goals of precision management in agriculture, and heavy metals, such as potassium, sodium, and calcium, may affect the absorption and transport of nutrients in crops. Research on the rapid detection of heavy metals and information acquisition techniques is urgently needed for the realization of precision agriculture (Gebbers and Adamchuk 2010).

Atomic absorption spectrometry (AAS), inductively coupled plasma optical emission spectroscopy (ICP-OES), and inductively coupled plasma with mass spectrometry (ICP-MS) are the common methods used to detect concentrations of heavy metal in crops (Peng et al. 2016). Although required accurate levels are reached, complex pretreatments are needed to apply these methods. The pretreatment process involved in using these methods requires a high-temperature and high-acid environment that can transform the organic structure in plants into inorganic structure, thus obtaining an aqueous solution containing only elements. In order to reduce damage to the costly instruments, the aqueous solution produced in such a manner needs to be filtered when entering the abovementioned instruments. Though these processes are deemed as rigorous and accurate, they are costly and time-consuming at the same time (Peng et al. 2018). It is apparent that the above drawbacks set limits on the real-time monitoring and rapid detection of heavy metals that can regulate heavy metal contamination and, in turn, guarantee efficient crop growth.

Existing technologies for the rapid detection of heavy metals are mainly spectral. LIBS is an atomic analysis spectroscopy that directly detects elements in crops and comes with an explained detection mechanism, whereas hyperspectral is a molecular spectrum that mainly uses heavy metal ions to chelate biomacromolecules with other substances in crops and fails to explain its mechanism.

Toxic heavy metal cadmium (Cd) is one of the most toxic heavy metals in paddy fields worldwide, because it is ubiquitous in the environment and highly toxic to humans (Mahmoud and Fawzy 2015). Because Cd could pollute water, soil, and other substances, it makes Cd to easily accumulate in crops. Certain soil may also contain an excessive accumulation of Cd due to the release of waste, the usage of chemical fertilizers and pesticides, and sewage sludge in agricultural lands (Mahmoud et al. 2016). There is no doubt that Cd easily enters the human body through the food chain and heightens the risk of cancer, mutation, endocrine disorder, renal failure, and chronic anemia (Ali et al. 2013). Therefore, having some practical means to monitor the heavy metal pollution level is essential for controlling the pollution.

Lettuce has been reported as having comparatively high accumulation of cadmium in its leaves, and it was proposed that lettuce should be used as an indicator plant to supervise the growth environment to decrease the risk associated with Cd toxicity. Shen et al. (2018) achieved rapid and accurate detection of heavy metal Cd contamination in lettuce using LIBS. Three Cd emission lines Cd II 214.44 nm, Cd II 226.50 nm, and Cd I 228.80 nm were selected to establish the univariate analysis model. As shown in Fig. 5.17, LIBS intensity in Cd II 226.50 nm performed the best with Rp^2 value of 0.9566 and limit of detection (LOD) = 2.9 mg·kg^{-1}. Multivariable analysis outperformed univariable analysis by PLS models based on full spectra: Rc^2 and Rp^2 were 0.9494 higher. Based on a PLS model, the best prediction result was achieved by 22 variables selected via genetic algorithm (GA) with Rp^2 = 0.9716 and the LOD = 1.7 mg·kg^{-1}. It is noteworthy that 18 variables in the 22 variables were featured on the left and right sides for the 3 strong Cd emission lines. K-nearest neighbors (KNN) and random forest (RF) models based on full LIBS spectra, Z-score LIBS full spectra, and variables selected by PCA loadings could be used to rapidly diagnose five levels of Cd contamination lettuce leaves.

Relying on laser-induced breakdown spectrometry, Liu et al. (2018a) investigated some newly developed variable index and chemometrics for the fast detection of cadmium (Cd) in tobacco root samples. Cadmium easily multiply in tobacco, and human exposure to Cd via smoking may exceed that caused by food, which is particularly true in the case of some heavy smokers. As shown in Fig. 5.18, results of

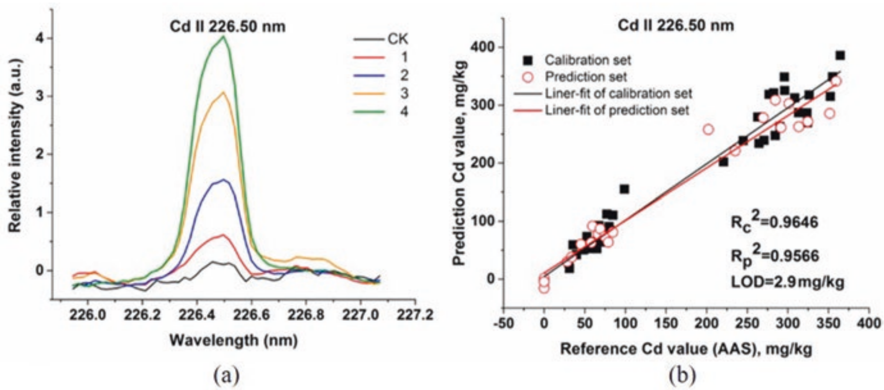

Fig. 5.17 Cd emission lines (**a**) Cd II 226.50 nm peaks. (**b**) Corresponding univariate analysis curve fitting plots

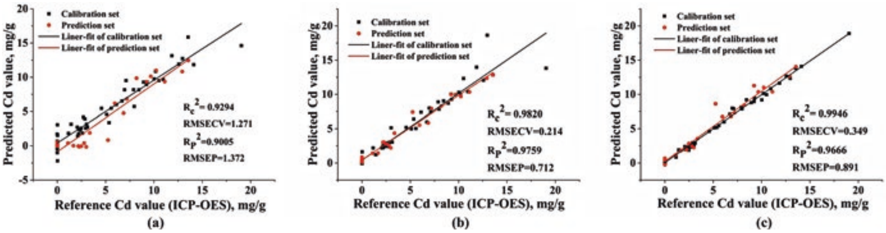

Fig. 5.18 The relationship between reference Cd value and LIBS measured Cd value predicted by SVM models based on (**a**) 22015 variables if the full spectra; (**b**) 1694 variables selected by the iPLS; (**c**) five variables selected by the BiPLS-SPA

multivariate analysis produced the most satisfying quantitative model with the iPLS-SVM model (R_c^2 of 0.9820, RMSECV of 0.214 mg·g^{-1}, R_p^2 of 0.9759, and RMSEP of 0.712 mg·g^{-1}) using the maximal relevant variables in the range of 474~526 nm.

Two new variable indexes were also developed to remove negative effects for Cd content prediction, including $Index_1 = (I_{508.58} + I_{361.05}) - 2 \times I_{466.23}$ and $Index_2 = I_{508.58}/I_{466.23}$, based on Cd emission lines at 508.58 nm, 361.05 nm, and 466.23 nm. Model based on $Index_2$ yielded better result with R_p^2 of 0.9502 and RMSEP of 0.988 mg/g. PLS and support vector machines (SVM) were adopted and compared for multivariate analysis. The results indicated that LIBS, coupled with the newly developed variable index and chemometrics, can provide a feasible, effective, and economical approach for the fast detection of cadmium in tobacco roots, which is conducive for the supervision of tobacco growth and quality safety.

Chen et al. (2019) improved the performance of the model by enhancing the heavy metal Cd signal in the laser-induced breakdown spectroscopy. A total of 20 sample pellets with Cd stress were prepared after the pyrolysis of lettuce powder. Cd signal was enhanced after pyrolysis. With respect to the PLS and SVR model based on full spectra after pyrolysis, the improvement achieved by airPLS preprocessing method was negligible. The PLS model after pyrolysis performed better with R_c^2 and R_p^2 values of 0.9973, RMSECV of 12.2 mg·kg^{-1}, and RMSEP of 13.3 mg·kg^{-1} with LOD = 0.8 mg/kg. The above results indicate that pyrolysis can improve the stability of signals and sensitivity of LIBS detection for Cd in tobacco.

Feng et al. (2019) studied rapid detection of cadmium and its distribution in *Miscanthus sacchariflorus* based on visible and near-infrared hyperspectral imaging. A competitive adaptive reweighted sampling (CARS) method was used for selecting optimal wavelength. A CARS-partial least squares regression model could offer accurate predictions of Cd contents in *M. sacchariflorus* leaves, with a determination coefficient (R^2) of 0.87 and a root mean square error (RMSE) value of 97.78 for the calibration set and an R^2 value of 0.91 and a RMSE value of 75.95 for the prediction set. They have also found that a CARS-least squares-support vector machine model could provide satisfactory predictions of Cd contents in roots, with R^2 values of 0.95 for the calibration set and 0.90 for the prediction set.

Peng et al. (2019) attempted to use dual-pulse laser-induced breakdown spectroscopy (DPLIBS) together with chemometric methods to predict chromium content in rice leaves. Two important parameters inter-pulse delay time and energy ratio for LIBS were optimized as 1.5 μs and 1:3 (the sum of first and second pulses was 80 mJ), respectively. The DPLIBS element signal strength is higher than single-pulse laser-induced breakdown spectroscopy (SPLIBS). The global spectrum of both SPLIBS and DPLIBS ranges from 240 to 860 nm, including 20,974 variables. The PLS models based on global spectra of DPLIBS outperformed that of SPLIBS. For DPLIBS, the R_p, RMSEP, and residual prediction deviation (RPD) in prediction set were 0.9928, 6.24 mg·kg^{-1}, and 7.54, respectively. In light of SPLIBS, the R_p, RMSEP, and RPD in the prediction set were 0.9729, 10.73 mg·kg^{-1}, and 4.39, respectively, and the values of regression coefficients were used to select feature variables. The selected variables contributed the most were emissions of chromium, including Cr I 357.87 nm, 359.35 nm, 360.53 nm, 425.43 nm, 427.48 nm, 428.97 nm, 520.60 nm, and 520.84 nm. The SVM model based on feature variables from DPLIBS yielded the best result, with R_p of 0.9946, RMSEP of 4.85 mg/kg, and RPD of 9.70 in the prediction set. The results indicate that using DPLIBS and chemometric methods to detect chromium content in rice leaves is a quite promising a method.

Heavy metal pollution in agricultural environment is extremely harmful, which has seriously restricted the quality and safety of agricultural products and sustainable development of green agriculture. Spectroscopy techniques can rapidly, accurately, and intuitively monitor crop physiological information and heavy metal element content, providing theoretical guidance for timely and effective monitoring of crop stress effect. At the same time, spectroscopy techniques have important scientific significance and application value for the management, regulation, prevention, and treatment of heavy metal stress in crops.

5.6 Crop Pesticide Residue Detection

Pesticides enter grain, vegetables, fruits, fish, shrimp, meat, eggs, and milk, causing food pollution and endangering health. The speed at which general organochlorine pesticides, primarily concentrated in fat, travel in the human body metabolism is quite slow, and it takes a long period of time for them to accumulate. Because of the great harm of pesticide residues to human beings and biological beings, the use of pesticides is strictly managed across the world, and the maximal level of pesticide residues in food has been stipulated in law.

5.6.1 Terahertz Technology for Residue Detection

Terahertz (THz) technology as a tool for pesticide detection and analysis has been proved by many studies. Massaouti et al. (2013) used THz time-domain spectroscopy (THz-TDs) to detect harmful chemical residues (sulfadiazine, sulfathiazole, tetracycline, coumaphos, and amitraz) in honey. These chemicals were characterized in the frequency range of 0.5~6.0 THz, and obvious absorption peaks were found. Their studies also showed that it is possible to trace the antibiotic residues in honey. Maeng et al. (2014) applied THz spectroscopy for determining mixed pesticide residues in wheat flour and found that the absorption spectra of seven pesticides were at 0.1~3 THz band. There existed a linear relationship between adsorption coefficient and the content of pesticide residues. Baek et al. (2016) studied the feasibility of detecting methomyl residues in food substrates (wheat and rice flour) based on THz-TDS and discovered that methomyl had three absorption peaks at 1.00, 1.64, and 1.89 THz. When the peak value of Baek analysis was 1.00 THz, the regression coefficient of the standard curve was greater than 0.974, the detection limit was less than 3.74%, the recovery was 78.0~96.5%, and the relative standard deviation was 2.83~4.98%. These researches demonstrate that THz technology is promising in the field of biological science. The THz-TDS system was used for spectral analysis of the pyrethroid pesticide samples. The system consisted of ultrashort pulse fiber laser, laser-gated photo-conductive semiconductor emitter, and laser-gated photo-conductive semiconductor receiver. The central wavelength of the ultrashort pulse fiber laser pulse was 780 nm, the pulse width was 90 fs, and the scanning precision was 50~150 μm. Specific absorption peaks were observed in the processed THz spectra of the three pesticides. The density functional theory (DFT) was used to characterize the molecular dynamics and formation mechanism of the absorption peaks. Deltamethrin had three peaks at 0.90, 1.49, and 2.32 THz. Fenvalerate had five peaks at 1.13, 1.43, 1.61, 1.98, and 2.58 THz, and beta-cypermethrin had four peaks at 1.27, 1.84, 2.12, and 2.92 THz.

Figure 5.19 shows the THz multivariate spectral characteristics and the molecular dynamics of three pyrethroid pesticides, including deltamethrin, fenvalerate, and beta-cypermethrin (Qu et al. 2018b). Based on the characterized fingerprint absorption peaks, a linear addition model was used to simulate the THz spectra of mixed pesticides. It was demonstrated that the simulated spectra of multicomponent pesticides agreed with those obtained by THz-TDS. The composition and concentration of multicomponent pesticides can be determined by analyzing the absorption peaks of THz spectra (Fig. 5.20). For the mixtures of two or three kinds of pesticides, the spectral correlation coefficients are higher than 0.9222, and the cosine angles are less than 22.75°. The proposed strategy led to an analytical methodology for studying the THz spectral characteristics of pesticides.

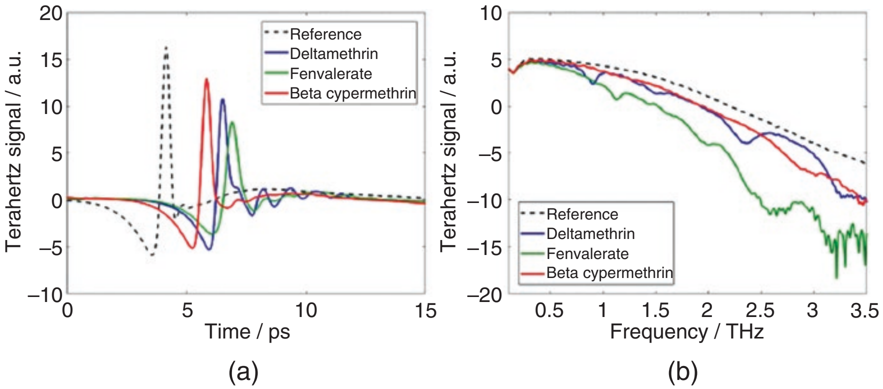

Fig. 5.19 THz spectra of reference and pesticides. (**a**) Time-domain spectra. (**b**) Frequency-domain spectra

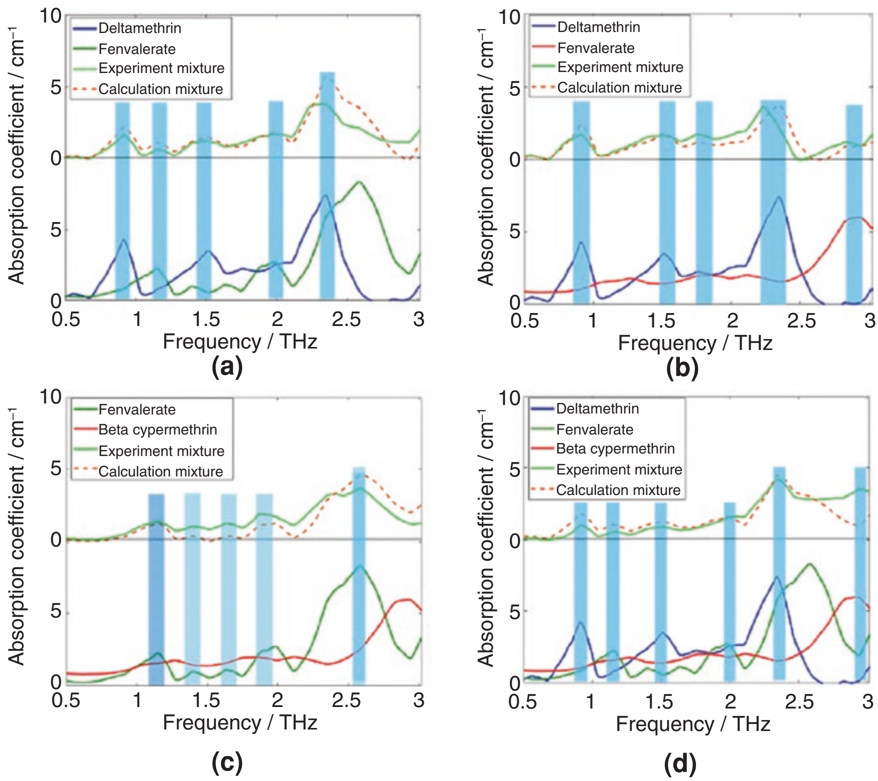

Fig. 5.20 The measured and simulated spectra of pesticide mixtures. (**a**) The mixture of deltamethrin and fenvalerate. (**b**) The mixture of deltamethrin and beta-cypermethrin. (**c**) The mixture of fenvalerate and beta-cypermethrin. (**d**) The mixture of deltamethrin and fenvalerate and beta-cypermethrin

5.6.2 Raman Technology for Residue Detection

Raman technology is also a promising method for residue detection in plants and agricultural products. He et al. (2014) measured the pesticide residue in apple using a surface swab capture method followed by surface-enhanced Raman scattering (SERS), and it was revealed that the swab-SERS method had a number of apparent advantages that included simplicity, sensitiveness, and short period (10 min) and that the method can be used to achieve quantitative detection of pesticide residues in fresh agricultural products, such as carrots, pears, and melons. Lin et al. (2015) studied the Raman spectroscopic properties of thiabendazole pesticides by attaching a layer of silver nanoparticles to the surface of the tested pesticides using SERS technique. This research suggested that 782, 1012, 1284, 1450, and 1592 cm^{-1} can be recognized as Raman characteristic peaks of the thiabendazole pesticides. Lasalvia et al. (2014) studied the Raman spectra of human neurons and epidermal cells that contacted with a mixture of chlorpyrifos and deltamethrin insecticides. It was concluded that Raman spectroscopy can be used for the principal component analysis of human cells that are frequently exposed to chemical substances like deltamethrin pesticides.

Deltamethrin is widely used as it effectively controls pests that interfere with the growth of strawberry and other fruits, including spiders, aphids, larva, etc. Thus, it is of great practical significance to accurately and rapidly detect whether the residues of deltamethrin in strawberry exceed the standard. Dong et al. (2018) investigated the use of surface-enhanced Raman spectroscopy to detect deltamethrin in strawberry. By applying density functional theory (DFT) and using gold nanoparticles (AuNPs) and silver nanoparticles (AgNPs) to enhance the Raman spectroscopy detection signal, they found that there were multiple bands, such as 554, 736, 776, 964, 1000, 1166, 1206, 1593, 1613, and 1735 cm^{-1} (Fig. 5.21), that could be determined as deltamethrin characteristic peaks, among which only three Raman peaks (736, 1000, and 1166 cm^{-1}) could be used as the deltamethrin characteristic peaks of strawberry when the detection limit reached 0.1 $mg \cdot L^{-1}$.

The frequency of the light absorbed overlaps the oscillation frequency of the electron, which leads to the enhancement of the oscillation of the metal electronic system. Monitoring of surface plasmon resonance (SPR) wavelength can be carried out at ease through UV/visible spectroscopy.

5.6.3 LIBS Technology for Residue Detection

LIBS technology is a newly arising technology for fast detection of pesticide residues in plants and agricultural products. Kim et al. (2012) suggested that the LIBS technique with the chemometric method (PLS-DA) can be a sound tool used to distinguish pesticide-contaminated samples from pesticide-free samples in a rapid manner, even though they share similar elemental compositions. By applying the

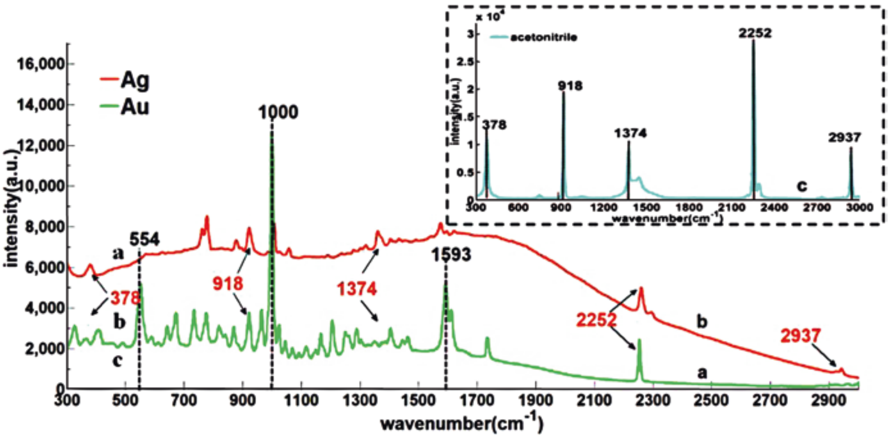

Fig. 5.21 The SERS of deltamethrin solution. (a) AuNPs, (b) AgNPs, and (c) acetonitrile

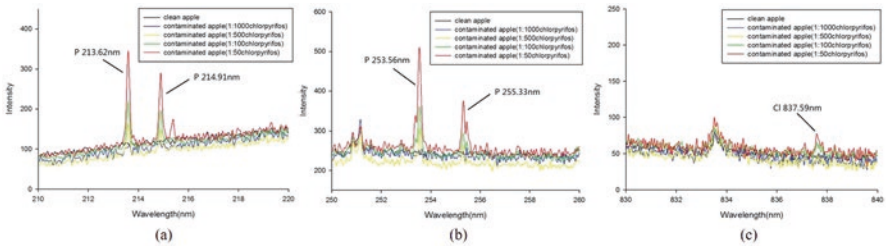

Fig. 5.22 LIBS spectra of chlorpyrifos solutions with different dilution ratios (1:50, 1:100, 1:500, 1:1000). (**a**) The characteristic peak of P at 213.62 nm and 214.91 nm. (**b**) The characteristic peak of P at 253.56 nm and 255.33 nm. (**c**) Characteristic peak of Cl at 837.59 nm

PLS-DA model established from the training set of data to predict the classes of test samples, misclassification rates were found to be 0% and 2% for clean spinach and pesticide-contaminated spinach, respectively. Multari et al. (2013) used LIBS to differentiate samples contaminated with aldrin, 1,2,3,4,6,7,8-heptachlorodibenzo-p-dioxin, chlorpyrifos, and the dieldrin in the complex matrices of tissue fats and rendering oils was described. What is noteworthy is that all samples were successfully differentiated from each other and from control samples. Sample concentrations can also be differentiated in relation to all pesticides, and the dioxin was also included in this study.

Du et al. (2015) explored the detection of chlorpyrifos residues on apple surfaces by laser-induced breakdown spectroscopy (LIBS). The researchers applied 100 ml chlorpyrifos solution with various concentrations on the surface of apple skin and then dried it in natural environment for about 30 minutes. They observed the characteristic peaks of P at 213.62 nm, 214.91 nm, 253.56 nm, and 255.33 nm and the characteristic peak of Cl at 837.59 nm, an effort that will provide a reference for quantitative detection. As illustrated in Fig. 5.22, the Cl and P peaks in the LIBS signal spectrum of apple samples are contaminated with chlorpyrifos solution at different concentrations (1:50, 1:100, 1:500, 1:1000). From Fig. 5.22a, b, it can be seen that the intensity of LIBS characteristic peak varies in stages. In addition, the strength of LIBS signal increases as solution concentration increases. Moreover, their research also found that the minimum detection limit was 1.5 mg·kg^{-1}.

5.7 Summary

Visible and near-infrared hyperspectral imaging, hyperspectral imaging, and chlorophyll fluorescence imaging have been adopted as non-destructive sensing technologies for the detection of crop nutrient and physiological status. The scope of detection covers malondialdehyde, soluble protein content, and pigment. The WinRHIZO root analysis system and scanning electron microscope were used to obtain root morphological parameters and microstructure of rice under heavy metal stress. MATLAB GUI interface was developed for batch processing of optical data of maize (*Zea mays*) leaves. Hyperspectral imaging technology, laser-induced breakdown spectroscopy (LIBS) technology, and thermal infrared spectroscopy were tapped into for the detection of crop diseases. LIBS was used to detect crop heavy metals, and terahertz technology, Raman technology, and LIBS were applied to detect the residues in crops. Based on the above research, a conclusion can be drawn that spectral technology has a great potential for application in the field of crop nutrient and physiological detection, morphology detection, disease detection, heavy metal detection, and pesticide residue detection. These rapid detection methods and technologies are essential for dynamic crop growth monitoring and precision management in agricultural Internet of things.

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Chapter 6
Field Condition Sensing Technology

Hui Fang, Yong He, Qin Zhang, Jinnuo Zhang, and Yongqiang Shi

Abstract With the rapid development of sensing, digital signal processing, and Internet communication technologies, many novel sensors, as well as essential components to IoT-based monitoring systems, have emerged and are continuing to emerge. Those sensors and networking components could help to achieve high sensitivity, improved adaptability, and enhanced reliability in monitoring field conditions for more efficient and productive agricultural productions. This chapter will introduce some commonly sensing technologies for measuring field environmental parameters, such as temperature, humidity, light, photoelectric, carbon dioxide, and microclimate parameters, such as wind speed and direction, rainfall, evaporation rate, and radiation, for effective field condition monitoring.

Keywords Field condition monitoring · Field environment sensing · Microclimate sensing · IoT-based monitoring system

6.1 Introduction

To achieve precision farming, one essential requirement is to apply the right amount of right resources to the right place at the right time. Doing so often demands knowledge about the field conditions, including environmental and microclimate conditions. This goal can be reached by using IoT-based monitoring system. If the production is conducted in a controlled environment, an IoT-based environment monitor/control system would allow farmers to optimize the environmental parameters, so that needs of crop growth at different stages would be met, thus fostering the optimal growing environment for crops and saving material and

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manpower at the same time (Tzounis et al. 2017). However, success in achieving such a goal still relies on adequate sensors that are connected to the IoT monitor/control systems (Manyika et al. 2015).

There are many types of agricultural sensors, among which environmental sensors such as temperature sensor, humidity sensor, photoelectric sensor, and carbon dioxide sensors are commonly used. It's important to note that farmland microclimate has a significant impact on agricultural production due to its basic characteristics (including the distribution of light, temperature, humidity, wind, and carbon dioxide in the farmland). At present, with the rapid development of sensor technology, sensors of wind speed, wind direction, rainfall, evaporation, and radiation have emerged for different characteristics of the farmland microclimate. However, agricultural sensors need to work in various harsh environments, so many sensors have poor adaptability, stability, and reliability under agricultural application conditions. For example, an air humidity sensor often works in an environment with a humidity above 95% in a greenhouse, which exceeds the environmental conditions for the normal operation of the sensor itself. How to overcome the adaptability of sensors in agricultural applications is an important breakthrough in agricultural information sensing.

6.2 Definition and Composition of Sensors

According to the Chinese National Standard GB 7665-87, sensor is defined as "A device that can sense a specified measured substance and convert it into a usable output signal conforming to a certain rule." The basic function of sensors is to detect and convert signals. Ideally, a functioning sensor, in terms of input, should be sensitive on a selective basis, i.e., sensitive only to the specified physical quantity. For example, a temperature sensor should only react to temperature changes and not to any other factor. Similarly, in relation to output, it should produce easily transmittable and processible such electrical or optical signals. With respect to the relationship between input and output, a functioning sensor should maintain a stable input-output relationship and a mathematically describable pattern under all application scenarios, which is to say that both consistent static characteristics and dynamic characteristics should be in place.

As the tools used to acquire the desired information, sensors play a decisive role in acquiring correct and accurate information. To achieve this, sensors are often built in three parts: a sensing element, a signal transforming element, and a signal conditioning circuit. Sometimes an auxiliary power source is also required to provide the energy that is needed, as shown in Fig. 6.1.

The sensing element in this system directly senses the measured value (generally non-electrical quantity) and converts it into certain physical quantities using specially designed selective sensing components. It is then converted, via the conversion element, into electrical parameters that include voltage, current, resistance, inductance, or capacitance. At last, a signal conditioning circuit converts

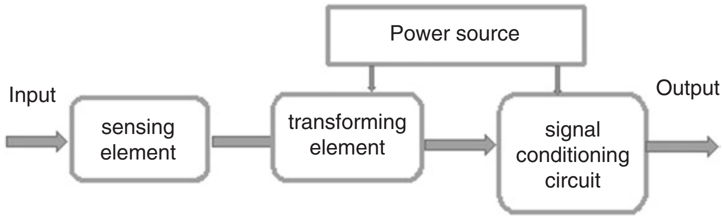

Fig. 6.1 General sensor detection structure

this electrical parameter into a form that can be further transmitted and processed. In a nutshell, sensor is a generic term for a component or device that converts the non-electricity to be measured into a corresponding electrical signal.

Sensors are widely used in the field of automation and artificial intelligence. Similar to the perceptive ability of human being, sensors are the essential elements for acquiring information on the operational scenario in an automated system. To a certain extent, the capability of a sensing unit can greatly influence the capability and/or performance of and automatic control or an artificial intelligence system.

6.3 Farmland Environment Sensors

Various types of sensors can be used in IoT-based farmland environmental parameter monitoring. One parameter often can be measured using different sensors, and similarly sensors working under the same principle can be used to measure different physical parameters. This section will introduce some commonly used sensors for different environmental parameters.

6.3.1 Temperature Sensors

Temperature measurement plays a major role in industrial production and our day-to-day life. In scientific research, environmental protection, and industrial and agricultural production, temperature sensors are mainly used for temperature measurement. As is generally known, temperature sensor refers to a sensor that can sense temperature and convert it into a usable output signal. According to the contact method of the temperature sensor and the measured medium, temperature sensor can be divided into two categories: contact type and non-contact type.

The contact temperature sensor ought to maintain thermal contact with the measured medium, so that the two can conduct sufficient heat exchange to reach the same temperature. This type of sensor mainly includes resistance temperature sensors, PN junction temperature sensors, thermoelectric temperature sensors, etc. The merits of the contact temperature sensor include simple structure, reliable operation, high measurement accuracy, sound stability, and low costs. Its disadvantage is that there is a large hysteresis (due to sufficient heat exchange during temperature measurement), which is inconvenient for movement. Additionally, the temperature field of the measured object is easily affected by the sensor, and the temperature measurement range is determined by the properties of the material used to build the temperature sensing element.

The non-contact temperature sensor, on the other hand, does not have to be in contact with the measured medium: the signal is transmitted to the temperature sensor through the heat radiation or convection of the measured medium. This type of sensor mainly includes infrared temperature sensor, fiber-optic temperature sensor, etc. Non-contact temperature sensors impose no limitation of measurement hysteresis and temperature range. They can be used to measure high temperature; the temperature of corrosive, toxic, and moving objects; and solid and liquid surfaces without affecting the temperature field of the measured object. Notwithstanding the above, non-contact temperature sensors are easily affected by the thermal emissivity of the measured object, their measurement accuracy is low, and the measurement distance and the intermediate medium exert greater impact on results. Many types of temperature sensors are available for application, and many of them fall in the following categories, namely, resistance, infrared, and optical fiber sensors.

6.3.1.1 Electronic Temperature Sensors

Electronic temperature sensors are widely used in many automatic temperature measurement applications and normally fall into two classes: resistive or thermoelectric. Resistive temperature sensors may be either metallic or semiconductor devices, and thermoelectric sensors (i.e., thermocouples) are self-generating transducers; both need having some forms of bridge circuit for signal amplification and conditioning, either built-in the sensor or as an additional signal conditioning device to which the sensor is connected to.

Resistive temperature sensors are probably the most common type in use, with the semiconductor versions being less expensive than the metallic version, and therefore may be more popular in many applications. Resistive-type temperature sensors are also known as the “resistance temperature detector (RTD)”. In general, metallic-type RTDs offer better performance than semiconductor counterparts and may be preferred if high accuracy is required.

Semiconductor type of RTPs are often manufactured as thermistors, made by combining two or more metal oxides, in different shapes of bead, disc, rod, etc. for convenient of using. Thermistors are, in general, very sensitive so they can detect small temperature changes; however, their accuracy is not as good as that of a metallic RTD. Thermistors can be used within the temperature range from −60 °C to +150 °C. The accuracy can be as high as ±0.1%.

Another very commonly used, and probably the most inexpensive, type of resistive temperature sensor is the thermocouples. As a self-generating transducer, it comprises two or more junctions between dissimilar metals, with one junction placed at a known reference temperature and the other junction at the place where the temperature is to be measured. One big advantage of using thermocouples is that their wide temperature can be covered. By selecting different types of thermocouples, it is possible to measure temperatures from −180 °C to +1200 °C. However, their sensitivity is in general not as good as thermistors. Furthermore, the accuracy is heavily dependent on the constancy of the referencing temperature being maintained during the measurement.

6.3.1.2 Infrared Temperature Sensors

In nature, any object with its temperature above absolute zero will constantly emit infrared radiation into the surrounding environment. According to the three major laws of radiation, Kirchhoff's law, Planck's law, and Wien's formula, the amount of infrared radiation energy emitted from an object and its distribution by wavelength are closely related to its surface temperature. Infrared temperature sensor is a sensor designed according to the principle that the radiant energy of an object changes with its temperature. As a long-range and non-contact way of temperature measurement, infrared temperature measurement is particularly suitable for measuring the temperature of high-speed moving objects, charged objects, and high-temperature and high-pressure objects. In addition, this type of sensors does not require thermal equilibrium. It can get the temperature of the object to be measured as long as its infrared radiation can be detected. The reflection time is generally at the millisecond level or even the microsecond level. Furthermore, infrared temperature measurement boasts high sensitivity. Since the radiant energy of an object is proportional to the fourth power of temperature, a small change in the temperature of an object will double the radiant energy, and the infrared sensor can quickly detect it. Its measurement accuracy can reach within 0.1 °C or smaller, and it can measure the temperature range from minus ten degrees Celsius to thousands of degrees Celsius. The temperature range of common infrared radiation thermometers is −30 °C to 3000 °C, and demand-specific specifications can be selected. In addition, the infrared thermometer is also particularly suitable for measuring the temperature of corrosive media and moving objects without destroying the temperature field of the measured object.

6.3.1.3 Optical Fiber Temperature Sensor

Optical fiber temperature sensor, a new type of temperature sensor developed in the mid-1970s, is the product of the rapid development of optical fiber and optical communication technology. This sensor is fundamentally different from electrical-based sensors. Due to the fact that fiber-optic sensors use light as the carrier of sensitive information and optical fibers as media for transmitting sensitive information, these sensors share the characteristics of both optical fiber and optical measurement. Fiber is resistant to corrosion and can be used in water, solutions, and chemical gases. In particular, because fiber is not affected by electromagnetic induction, sparks are not a concern, which is also why it can be measured normally in flammable and explosive environments such as coal mines, oil, and gas storages. Optical fiber temperature sensors have developed rapidly, forming a variety of products, and have been applied to many fields. According to the working principle, the optical fiber temperature sensor can be divided into functional type and transmission types. The functional optical fiber temperature sensor serves as the sensor and the carrier of the optical signal, while the transmission optical fiber temperature sensor only transmits the optical signal. At present, the main optical fiber temperature sensors include distributed optical fiber temperature sensors, fiber grating temperature sensors, and optical fiber fluorescence temperature sensors. Among them, the most widely used is distributed optical fiber temperature sensor. And its measurement distance can reach up to 30 km, the measurement accuracy can reach up to 0.5 °C, the spatial positioning accuracy can reach up to 0.25 m, and the temperature resolution can reach up to about 0.01 °C.

6.3.2 Humidity Sensors

Humidity sensors sense the water vapor content of a gas and convert it into a usable output signal (Farahani et al. 2014). In an agricultural context, because humidity is easily affected by other factors, such as atmospheric pressure and temperature, it is a parameter that is the most difficult to accurately determine. There are a number of traditional methods for measuring humidity, such as thermodynamic methods, coagulation methods, electromagnetic wave methods, moisture absorption methods, and so on. However, such methods fail to meet the development needs of modern technology. In recent years, humidity-sensitive sensors witnessed rapid development, advancing from simple humidity-sensitive elements to integrated, intelligent, and multi-parameter detection.

As the simplest humidity sensor, humidity-sensitive element can be divided into two types: resistance and capacitance. The characteristic of the humidity-sensitive resistor is that the substrate is covered with a film made of a moisture-sensitive material. When water vapor in the air is adsorbed on the moisture-sensitive film, the resistivity and resistance of the element are changed. Though humidity sensors are highly sensitive, they suffer from drawbacks that include poor linearity and poor interchangeability of the product. Humidity-sensitive capacitors are generally made of polymer film capacitors. When the ambient humidity changes, the dielectric constant of the humidity-sensitive capacitor changes accordingly, and so dose its capacitance. Additionally, its capacitance change is proportional to the relative humidity. Humidity-sensitive capacitors boast high sensitivity, sound product interchangeability, fast response speed, small amount of hysteresis, easy manufacturing, and easy miniaturization and integration, yet their accuracy is generally lower than that of humidity-sensitive resistors.

6.3.2.1 Lithium Chloride Resistance Hygrometer

Lithium chloride hygrometers are composed of moisture-sensitive resistors and measuring instruments. Wet-sensitive resistance is an electrode wrapped on an insulated tubular frame, coated with a certain concentration of lithium chloride and polyvinyl alcohol mixture; after drying, a porous wet film is formed. Using the chemical properties of lithium chloride in moisture-sensitive film, which is easy to absorb moisture and release moisture, it can sense the humidity in air. When the partial pressure of water and steam in air is higher than that of water vapor in moisture film, the moisture-sensitive film will absorb water vapor and reduce the resistance value. On the contrary, when the partial pressure of water vapor in air is lower than that of water vapor in moisture-sensitive film, the moisture-sensitive film will release water vapor and make the resistance value rise.

As an ionic electrolyte salt, lithium chloride is highly hygroscopic and dehumidifying. The relative humidity in air is detected through the detection of the change in the resistance value of the moisture-sensitive material containing lithium chloride. The lithium chloride electric humidity sensor based on the principle of resistance-humidity characteristics was first developed by F.W. Dunmore of the American Bureau of Standards (Chen and Yang 1986). This kind of element comes with high precision, simple structure, and low cost.

The measurement range of the lithium chloride element is related to the lithium chloride concentration and other components of the moisture-sensitive layer, and the effective humidity sensing range of a single element is generally within 20% relative humidity (RH). For example, a 0.05% concentration corresponds to a humidity range of about 80–100% RH, a 0.2% concentration corresponds to a range of 60–80% RH, and so on and so forth. It can be seen that when measuring a wide range of humidity, components with different concentrations must be used jointly. The number of hygrometer combinations that can be used for full-scale measurement is generally five, while the measurable range of the lithium chloride hygrometer using the component combination method is usually 15–100% RH.

6.3.2.2 Lithium Chloride Dew Point Hygrometer

The lithium chloride dew point hygrometer was first developed by Foxboro Corporation, a US-based company. This type of hygrometer is similar to the abovementioned lithium chloride resistance hygrometer, yet its working principle is completely different. In a nutshell, this hygrometer functions using the saturated water vapor pressure of a saturated aqueous solution of lithium chloride as a function of temperature. Determine the dew point temperature of the air to be measured by measuring the temperature of the salt solution when the saturated water vapor pressure of the saturated lithium cyanide solution is equal to the water vapor pressure of the measured air. Then calculate the relative humidity of the air according to the dry bulb temperature and dew point temperature of the air.

The measurement range of the lithium chloride dew point humidity sensor can be from −45 °C to +60 °C dew point. When the air dew point temperature does not exceed +60 °C, the probe can be used in temperatures ranging from 100 °C to higher. When measured at 0 °C to +60 °C at room temperature, relative humidity ranges from 12% to 100%.

6.3.2.3 Carbon Humidity Sensor

Moisture-sensitive component is referred to as moisture-sensitive device, which refers to a class of electronic components easily affected by environmental temperature, humidity, and static electricity.

Advantages of the carbon humidity sensor, first proposed by Carver and Breasefield in the United States in 1942, include fast response, sound repeatability, zero erosion effect, and narrow hysteresis loop (Xu 2006). Carbon humidity sensors work by soaking plastic sheets in a mixture of chemicals such as carbon particles, Then dry it as a moisture sensitive film. When the relative humidity in the atmosphere increases, the moisture absorption of the membrane increases causing the volume expansion of membrane. The volume expansion makes the contact probability of the conductive carbon black particles decrease, which leads to the resistance of elements increases; On the contrary, the relative humidity decreases and the moisture sensitive film dehydrates, resulting in the shrinkage of the film volume, which increases the probability of the conductive carbon black particles contacting each other, leading to the reduction of the resistance value of the element.

China's meteorological department started with the development of carbon humidity sensors in the early 1970s and achieved positive results. More specifically, the measurement uncertainty does not exceed ±5% RH, the time constant is 2–3 s at positive temperature, and the hysteresis is generally between about 7%.

6.3.2.4 Alumina Hygrometer

Alumina hygrometers are generally composed of a sensor, a sensing element, an electrical parameter measuring unit, and a display. The aluminum oxide sensor is actually a flat plate capacitor with aluminum substrate and gold film as the poles and porous aluminum oxide layer as the medium by chemical anodic oxidation. The porous alumina tube structure and the gold film which can permeate water molecules lay a good foundation for the moisture measurement. It has been proved that the moisture measurement of alumina moisture sensor is based on physical adsorption. It works by placing components in the gas path being measured. Water molecules will quickly through the whole film, and is adsorbed in the pore wall of alumina. It reaches a dynamic adsorption equilibrium with the water pressure in the space around the electronic component, and then causes changes in the dielectric constant, capacitance and resistance of the component. The changes in these electrical parameters of the component can be used to determine the water content in the gas.

Alumina sensors feature advantages that include small size (such as 90 μm thick and 12 mg weight for humidity sensors used in radiosondes), high sensitivity (lower measurement limit of −110 °C dew point), and fast response speed (typically 0.3–3 s). The measurement signal is directly produced in the form of electrical parameters, significantly simplifying the data processing program. In addition, alumina hygrometers can also be used to measure moisture in liquids. The above characteristics are exactly what certain measurement fields in industry and meteorology require and are the reason why people show great interests for the method. Therefore, alumina hygrometers are considered as one of the applicable sensors for high-altitude atmospheric detection.

6.3.3 Light Sensors

Light sensor is used to measure light intensity, "illumination" for short. The number of lumens (lm) per square meter is referred to as illuminance, which is a unit that reflects the intensity of light. Its physical meaning is the luminous flux that shines onto a unit area.

Photoelectric sensor technology mainly uses the optical effect of the measured object. It collects the optical signal of the measured object and converts the optical signal into electrical signal for signal transmission and analysis. The technology is widely used and has a good prospect in agriculture. Current agricultural greenhouse automation degree is not high and needs a lot of manpower money to monitor and maintain the crops, and the cost is high. With optical fiber transmission and embedded control, the photoelectric sensor can intelligently control the illumination, humidity, and carbon dioxide concentration in the greenhouse, which not only saves the labor cost but also makes the growth of crops in the greenhouse under the optimal environment all the time through scientific methods.

Photoelectric sensor is a sensor that uses a photoelectric element as a detection element and converts luminous flux into electricity. The basis for such sensors is the photoelectric effect of the photoelectric conversion element. The measured change is first converted into a change in the optical signal, and the optical signal is then further converted into an electrical signal by means of a photoelectric element. Photoelectric sensors, generally composed of three parts, light source, optical path, and photoelectric element, are non-contact, and they feature high precision, high resolution, high reliability, and fast response. Thanks to these characteristics, photoelectric sensors are widely used in the field of detection and control (Dutta 2019; Hou and Yao 2020; Jin et al. 2018).

Generally speaking, photoelectric sensors work in four ways: absorption, reflection, shading, and radiation. With respect to the absorption method, the measured object is located between the constant light source and the photoelectric element. The measured parameter is determined by the degree of light absorption of the measured object or the selection of its spectral line, such as the transparency measurement of liquids and gases. In terms of the reflection method, the light emitted by a constant light source is projected onto the measured object, which reflects part of the light flux onto the photoelectric element, and the surface state and property of the measured object are determined according to the reflected light flux. For example, the reflection method can be used to measure the surface roughness, surface defects, and surface displacement of parts (Li 2004). Regarding the light-shielding method, the measured object is located between the constant light source and the photoelectric element. A part of the light flux emitted by the light source is blocked by the measured object, so that the luminous flux acting on the photoelectric element is weakened, and the degree of attenuation is the same as that of the measured object in the optical path that is related to location. This principle can be used to measure length, thickness, linear displacement, angular displacement, vibration, etc. Radiation means that the measured object itself is a radiation source, which can be directly irradiated on the photoelectric element, or it can act on the photoelectric element after a certain optical path. Photoelectric pyrometers, colorimetric pyrometers, infrared detection, and infrared remote sensing all fall into this category. This method can also be used for fire alarms and photometers.

6.3.4 Carbon Dioxide Sensors

Carbon dioxide is one of the raw materials for photosynthesis, which produces 95% of the dry weight of crops. Therefore, the adoption of carbon dioxide sensors for controlling concentration has become an important factor affecting crop yield. Plastic greenhouse cultivation keeps crops in a relatively closed place for a long time. The carbon dioxide concentration in sheds, changing drastically within the period of 1 day, reaches a maximum of 1000–1200 ppm before sunrise and drops to about 100 ppm, approximately equivalent to 30% of the atmospheric concentration, 2.5–3 hours after sunrise. Carbon dioxide concentration did not rise until 2 pm and did not return to atmospheric levels until around 4 pm. The carbon dioxide concentration required for vegetables is generally 1000–1500 ppm; therefore, carbon dioxide deficiency in the plastic greenhouse is quite severe. It is a problem that has become an important factor affecting the yield of vegetables in the plastic greenhouse. Installing a carbon dioxide sensor in a plastic greenhouse can ensure prompt alarm in the event of insufficient carbon dioxide concentration, so that gas fertilizers can be used to ensure the market availability of vegetables, edible fungi, flowers, and so on while ensuring quality and yield.

6.3.4.1 Carbon Dioxide Semiconductor Sensors

Carbon dioxide semiconductor sensors are mainly composed of metal oxide semiconductor materials. At certain temperatures, this type of semiconductor sensing equipment changes, to a certain extent, as the composition of the ambient gas changes. Related parameters of carbon dioxide in the air are then detected by the fluctuation of the resistance current in the sensing core. Based on semiconductor ceramic technology doped with CeO-AgNO3, Xiu et al. (2007) created a functional material that is sensitive to carbon dioxide gas and measured the temperature and humidity characteristics of the device. Kim et al. (2017) also built a semiconductor-type carbon dioxide sensor using cobalt oxide containing barium carbonate.

6.3.4.2 Carbon Dioxide Catalyst Sensor

Carbon dioxide catalyst sensors typically relied on a catalyst coating on the surface of a platinum resistor. At a certain temperature, the flammable gas catalyzes combustion on its surface, the platinum resistance temperature rises, and the resistance changes according to the function of the flammable gas concentration. Carbon dioxide catalytic combustion sensors detect flammable gases on a selective basis: anything flammable can be detected. The sensors do not respond to anything that are not flammable, which is why this kind of sensor is mostly used in metal smelting industry.

6.3.4.3 Carbon Dioxide Thermal Conductivity Sensors

Thermal conductivity sensor is a kind of thermal effect sensor. In the test process, no chemical reaction occurs with the gas to be measured, which avoids the material change caused by chemical reaction. Therefore, its output is stable and its drift is small.

The principle of a carbon dioxide thermal conductivity cell sensor is to make use of the unique thermal conductivity of each carbon dioxide gas. When the thermal conductivity of two or more gases significantly differs, the thermal conductivity element is used to distinguish the content of one of the components. Though widely used for the detection of hydrogen, carbon dioxide, and high-concentration methane, such sensors are limited by their narrow scope of application and many other factors. Additionally, carbon dioxide thermal conductivity cell sensors are old-fashioned products with manufacturers all over the world. In order to overcome the shortcomings of traditional thermal conductivity gas sensors, Febrina et al. (2019) developed a simple CO_2 sensor based on the thermal conductivity, which consists of a modified IR thermopile sensor without an IR window. The thermopile can simultaneously serve as a heater and temperature sensor and was used for measuring the CO_2 concentration.

6.3.4.4 Carbon Dioxide Electrochemical Sensors

Carbon dioxide electrochemical sensor is a kind of chemical sensor that converts the concentration (or partial pressure) of carbon dioxide into electrical signals through electrochemical reaction. It can realize continuous on-site monitoring and has the advantages of low price, compact structure and easy to carry, etc. It mainly includes potential type, current type, and electric quantity type.

A large number of the flammable, toxic, and harmful gases are electrochemically active, and the relevant parameters of carbon dioxide in the atmosphere can be distinguished by electrochemical oxidation or reduction, that is, by using these reactions of carbon dioxide gas and sensor sensing components. Such sensors usually have many functions, and sometimes they can be used to distinguish some gases other than carbon dioxide (Rowiński and Bilewicz 2001).

6.3.4.5 Carbon Dioxide Infrared Sensors

Carbon dioxide infrared sensors use the special characteristics of carbon dioxide in the infrared to detect the absorption of carbon dioxide by infrared to determine the concentration of a given gas (Zhang 2002). This kind of sensors used to be large analytical instruments, but in recent years, due to the development of the sensor industry based on MEMS technology, the volume of this sensor has been reduced from 10 L to about 2 ml (thumb size). The use of an infrared detector without a modulated light source makes the instrument completely free of mechanical moving parts and hence maintenance-free. Zhang (2002) proposed a new spatial dual-beam measurement structure and established a mathematical model of the sensor based on the RBF neural network. They designed a dynamic compensation filter and successfully developed a new type of high-performance infrared carbon dioxide sensor. Wang et al. (2016) proposed a carbon dioxide sensor based on mid-infrared absorption spectrum for greenhouse agriculture and deployed a sensor network. Zhang et al. (2010) developed a miniature sensor for measuring the concentration of carbon dioxide gas. In Zhang's research, a new type of space dual-beam optical detector was designed. The detector consisted of an infrared light source, an air chamber, an infrared receiving device, and two windows. The experiments demonstrate that the infrared sensor markedly improved the signal-to-noise ratio of the sensor (Zhang et al. 2010).

Taking as an example the application of carbon dioxide sensors in the production and cultivation of edible fungi, the following section seeks to provide the reader with a clear understanding of the important role played by carbon dioxide sensors in production. China's edible fungus production currently accounts for 65% of the world's total output, ranking first globally. However, the production of edible fungi in China is scattered among thousands of households. The small scale, poor conditions, and lack of technology have hindered further growth of the edible fungus industry. Control of production process is based on experience only, and monitoring facilities are extremely scarce, making the quality and safety of edible fungus products a major issue. In the production of edible fungi, air temperature, humidity, illuminance, and carbon dioxide and oxygen concentrations are the key factors that influence growth. Operation based on the individual experience of farmers alone will result in poor quality and low yield of edible fungi. Therefore, monitoring carbon dioxide, oxygen, temperature, and humidity in the context of edible fungus is essential for standardized management of edible fungus production. In this respect, using carbon dioxide sensors and oxygen sensors to monitor the environment is required. All edible fungi are aerobic fungi, and the oxygen supply and carbon dioxide concentration in the ambient air exert major influence on the growth of edible fungi. Generally, the aerobicity of mycelial growth is low, and a slightly higher concentration of carbon dioxide is conducive to primordium differentiation; however, in the growth stage of fruiting bodies, a large amount of oxygen supply is needed. The carbon dioxide concentration should be controlled below 0.1%, and if the concentration of carbon dioxide is excessive, the stem cap would be small, and the cap would even be undifferentiated and deformed. Therefore, carbon dioxide sensors can be used to accurately reflect the concentration of carbon dioxide in the environment, which is convenient for timely adjustment. Carbon dioxide-sensitive fungi include black fungus, *Ganoderma lucidum*, *Agaricus bisporus*, and mushrooms, while *Flammulina velutipes* and *Pleurotus ostreatus* are more resistant to carbon dioxide. In particular, when the carbon dioxide concentration is 0.06–0.49%, as the carbon dioxide concentration increases, the diameter of the lid decreases. Moreover, under such circumstances, the opening of the lid is suppressed, the extension of the mushroom stem is promoted, and the commercial value of the mushroom is improved.

6.4 Farmland Microclimate Sensors

As an important factor of affecting crop growth and yield, farmland microclimate refers to the small-scale climatic conditions formed within a particular land. It is generally expressed using wind, rainfalls, evaporations from soil and crop, and radiation. It is often an important piece of information for precision management of crop production, including predicting and preventing pests and diseases and preventing weather/climate-related crop damages or even disasters.

The physical basis for the formation of microclimates in farmland mainly consists of active surfaces and layers. The moving surface is the surface of the object with the most apparent heat and moisture exchange. A major role is played by the transport of material and the conversion of energy among farmland soil, plants, and the various components of the atmosphere in the formation of microclimates. In addition, the active surface is not the only layer that facilitate the basic physical functions of microclimate formation; layers with a certain thickness also contribute to this process. Such layers are referred to as the active layer or contributing layer.

The basic characteristics of farmland microclimates include the distribution of light, temperature, humidity, wind, and carbon dioxide in farmland. When solar radiation reaches the upper surface of farmland vegetation, part of it is reflected by the foliage, part of it is absorbed by the foliage, and part of it passes through the plant gap or penetrates through the foliage to the lower layers of ground. Different crops or the same crop at different growth periods differs in terms of their ability to reflect, absorb, and transmit solar radiation. The vertical distributions of total radiation intensity, direct radiation intensity, and scattering intensity in farmland are similar, all of which decrease progressively from the top of the plant. At the beginning, the speed of decrease is relatively slow, it then weakens rapidly in the middle layer, and then it resumes the same slow speed. Therefore, over-planted farmland is not conducive to light transmission in the lower layer, and cultivating appropriate plant types holds the key to the effective use of solar energy. The temperature distribution in the farmland hinges on the farmland radiation difference and farmland turbulence. The temperature distribution differs according to different crops, different growth periods, and cultivation measures; and the humidity distribution and change in farmland are determined by changes in temperature, farmland evaporation, and turbulent water vapor exchange intensity. The air turbulence in the daytime causes water vapor to evaporate upward, and at night the water vapor flows to the crop layer and condenses into dew or frost. Regarding the distribution of wind, judging from the horizontal distribution of wind speed, the wind speed continuously decreases from the side of the farmland to the middle of the farmland. The decrease is fast at the beginning, and it then slows down and stabilizes after reaching a certain distance. Seen from the vertical direction, wind speed is significantly weakened in the dense part of the leaves in the crop layer; at the place where the top and lower stems and leaves are scarce, the wind speed is high; and in the lower part of the crop layer farther from the side, it is low.

Due to effects of the adoption of different agricultural practices, different crops, and dynamic changes of crop groups in places of production that include farmland, greenhouses, and pastures, the conditions and various physical characteristics of the active surface of the farmland are constantly changing, resulting in changes of local radiation balance and heat balance, which in turn form various types of farmland microclimate characteristics. After the formation of a certain farmland microclimate, the environmental conditions for crop growth will directly affect the growth, development process, and yield of crops. The significance of studying farmland microclimate is to analyze the distribution and changing characteristics of farmland microclimate elements and to look for measures to improve crop growth environmental conditions (i.e., farmland microclimate conditions), so that these microclimate conditions would be conducive to crop growth and development and improve crops' yield and quality. At present, with the rapid development of sensor technology, various sensors, targeting different characteristics of farmland microclimate, have been developed for the continuous monitoring of environmental parameters closely related to vegetation and crop growth.

6.4.1 *Wind Sensors*

The wind, a natural phenomenon caused by the movement of air, is a product of solar radiation heat. From meteorology perspective, the wind often refers to the horizontal motion components of the air, including direction and magnitude, i.e., wind direction and wind speed; and it is also one of the environmental factors of production. As such, the measurement of wind speed and direction plays a major role in monitoring farmland microclimate. Sensors for wind speed and direction measurement are already available on the market.

6.4.1.1 Wind Speed Sensors

Wind speed sensor is a common sensor that can be used to continuously measure wind speed and wind volume (air volume = wind speed × cross-sectional area). Wind speed sensors are roughly divided into mechanical (mainly propeller type, wind cup type) wind speed sensors, hot wind specific speed sensor, and ultrasonic wind speed sensor based on acoustic principles.

Propeller Wind Speed Sensor

As shown in Fig. 6.2, the electric fan, driven by a motor to rotate the fan blades, creates a pressure difference between the front and rear of the blades to promote airflow. The working principle of the propeller anemometer is exactly the opposite of this. Aligned with the airflow is affected by wind pressure, the blade system generates a certain torsional moment, causing the blade system to rotate. Generally, a propeller-type speed sensor measures wind speed by rotating a set of three- or four-blade propellers around a horizontal axis. The propeller, whose speed is proportional to the wind speed, is usually installed at the front of a weather vane so that its rotation plane always faces the direction of the wind.

Fig. 6.2 Propeller wind speed sensor

Fig. 6.3 Wind cup-type wind speed sensor

Fig. 6.4 Thermal wind speed sensor

Wind Cup-Type Wind Speed Sensor

Wind cup-type wind speed sensor, a commonly used wind speed sensor, was first invented by Rubin Sun of the United Kingdom. As shown in Fig. 6.3, the sensing part consists of three or four conical or hemispherical empty cups, while the hollow cup shell is fixed on a three-pointed star bracket at a 120° angle or a cross-shaped bracket at a 90° angle. The concave surfaces of the cup are aligned in one direction, and the entire cross arm is fixed on a vertical rotation axis. When the wind cup rotates, the coaxial multi-tooth disc or magnetic rod is driven to rotate, and a pulse signal proportional to the speed of the wind cup is acquired through the circuit. The pulse signal is counted by a counter, and the actual wind speed value can be obtained after conversion. At present, the new rotating cup anemometer uses three cups, and the conical cup outperforms the hemisphere. When the wind speed increases, the rotating cup can quickly accelerate to adapt to the airflow speed. When the wind speed decreases, due to the influence of inertia, the speed drops likewise; however, the speed may not drop immediately. The wind speed indicated by the rotary anemometer in the gust wind is generally high, a phenomenon referred to as the excessive effect (the average error produced is about 10%).

Thermal Wind Speed Sensor

As shown in Fig. 6.4, thermal wind speed sensor adopts hot wire (tungsten wire or platinum wire) or hot film (film made of platinum or chromium) as probe. The sensor is exposed in the measured air and is connected to the Wheatstone bridge. By measuring the balance relationship of its resistance or current, the air flow rate of the measured section can be detected. Coated with an extremely thin quartz film insulation layer to insulate the fluid and prevent pollution, the thermal film of the thermal film-type wind speed sensor can work in air flow with particles, and its strength is higher than that of metal hot wire. The resistance, varying with temperature, and the temperature of the hot wire are in a normal temperature range (0–300 °C). The two illustrate a linear relationship. The heat dissipation coefficient is related to the airflow speed: the higher the flow velocity, the larger the corresponding heat dissipation coefficient, which means fast heat dissipation; and the slower the flow velocity, the slower the heat dissipation.

Hot wire wind speed sensor is equipped with two design circuits, constant current and constant temperature, the latter of which are more commonly used. The principle of the constant temperature method is to keep constant the temperature of the hot wire during the measurement process to balance the electric bridge. At this time, the resistance of the hot wire remains unchanged, and air velocity is only a single value function of the current. According to the relationship between the known air velocity and the current, velocity of the airflow at the end of the devise can be determined. The constant current hot wire wind speed sensor keeps the current value flowing through the hot wire from any changes during the measurement. When the current value is constant, the airflow speed is only related to the resistance of the hot wire. According to the known relationship between the airflow speed and the resistance of the hot wire, velocity of the airflow that travels through the wind speed sensor can be obtained. Additionally, pulsating wind speed is measured by the hot wire wind speed sensor. The constant-type wind speed sensor has a large thermal inertia, and the constant temperature-type wind speed sensor has a relatively small thermal inertia as well as a high-speed response. The measurement accuracy of the hot wire wind speed sensor is not high; thus, users should pay attention to temperature compensation when using the device.

Ultrasonic Wind Speed Sensor

The working principle of the ultrasonic wind speed sensor is to measure the wind speed using the ultrasonic time difference method. Due to the speed of sound in the air, it will be superimposed on the velocity of the wind. If the ultrasonic wave travels in the same direction as the wind, then its speed will increase; conversely, if the ultrasonic wave travels in the opposite direction to the wind, its speed will become slower. Therefore, under fixed conditions, the speed of ultrasonic wave propagation in the air corresponds to the wind speed function. One can acquire accurate wind speed and direction through calculation. As sound waves travel through the air, its speed is subject to temperature. The wind speed sensor detects two opposite directions on two channels, thus making the effect of temperature on the speed of sound waves negligible.

Fig. 6.5 Ultrasonic wind speed sensor

The ultrasonic wind speed sensor features light weight, zero moving parts, and ruggedness. Plus, the device does not require maintenance and on-site calibration, and it can produce wind speed and direction simultaneously. Customers can choose the wind speed unit, output frequency, and output format according to their own needs. One can also choose a heating device (recommended for use in cold environments) or analog output according to the specific needs. The sensor can be used together with computers, data collectors, or other acquisition equipment with RS485 or analog output. If necessary, multiple units can also be used in a network. Ultrasonic wind speed and wind direction instrument is a relatively advanced instrument for measuring wind speed and direction, and because the instrument overcomes the inherent shortcomings of the mechanical wind speed and direction indicator, it can work normally all day and for a long period and is used increasingly widely. The instrument can be a powerful alternative to mechanical anemometers (Fig. 6.5).

6.4.1.2 Wind Direction Sensor

The wind direction sensor is a physical device that detects the external wind direction information through the rotation of the wind direction arrow. The information is then transmitted to the coaxial code disc; at the same time, the corresponding value of the wind direction is produced. It is generally the case that the main body of the wind direction sensor adopts the mechanical structure of the wind vane. When the wind blows toward the tail fin of the wind vane, the arrow of the wind vane will point in the direction of the wind. In order to remain sensitive to direction, different internal mechanisms are also used to distinguish the direction for the wind speed sensor (Fig. 6.6).

Electromagnetic Wind Direction Sensor
Although the design of this device is based on the electromagnetic principle, its structure differs due to the adoption of many types of principles. At present, some of these sensors started to use gyro chips or electronic compasses as basic components, and the accuracy of measurement has been further improved.

Fig. 6.6 Wind direction sensor

Photoelectric Wind Direction Sensor
This wind direction sensor, adopting absolute Gray code disc as the basic element, uses a special customized coding. Based on the principle of photoelectric signal conversion, it produces accurate information of the corresponding wind direction.

Resistive Wind Direction Sensor
The structure used is similar to sliding rheostat, and the maximum and minimum resistance values are marked as 360° and 0°, respectively. When the wind vane rotates, the slider of the sliding rheostat will follow the wind vane on the top Rotate, and different voltage changes can be counted on for the calculation of the angle or direction of the wind direction.

In agricultural production, moderate wind speed holds the key to improving farmland conditions. Near-surface heat exchange, farmland evapotranspiration, and transportation of carbon dioxide and oxygen in the air are accelerated or strengthened in line with the increase of wind speed. In addition, wind can spread plant pollen and seeds to facilitate plant pollination and reproduction. However, wind also exerts negative effects on agriculture. For instance, wind spreads pathogens and plant diseases. Strong levels of wind cause mechanical abrasion of leaves, crop lodging, broken trees, flowers and fruits, reduced yield, wind erosion, sand dune movement, and farmland destruction. Blind reclamation in arid areas would lead to desertification. Moreover, strong winds and blizzards in pastoral areas can blow away herds and aggravate freezing damage. Some special characteristics of local winds often lead to wind-related damage. The tidal wind with high salinity from the sea and the high-temperature and low-temperature foehn wind and dry hot wind all pose critical threats to the flowering of fruit trees, fruit filling, and grain filling of cereal crops. Normal wind, on the other hand, is beneficial to agricultural production; thus, it is of great benefit to measure wind speed and direction. Timely monitoring of agricultural meteorology and the environment is therefore needed. One can use wind speed sensor for the monitoring of the wind speed and volume in real time and connect it with the data acquisition control module to acquire relevant data, which would be transmitted to the meteorological data analysis software through the wireless module for analysis and display, thus facilitating safe production.

6.4.2 Rainfall Sensors

Figure 6.7 is an illustration of a rainfall sensor, which is mainly composed of a water receiver, a filter funnel, a dump bucket, a reed switch, a base, and a special measuring cup. As a physical quantity that measures the magnitude of rainfall, precipitation measurement also represents a major element in meteorological observations, providing accurate and reliable data for weather forecasting, hydrology, scientific research, agriculture, forestry production, disaster prevention, and disaster reduction. After years of improvement and application, rainfall sensors have become increasingly advanced and accurate. Rainfall sensors that have been put into practical use include siphon, tipping, water-conducting and double valve capacity grid, etc. Among these, the first two types of sensors are the most widely used ones in China (Jiang et al. 2019). Thanks to continuous research and optimization, the tipping bucket rain sensor has become more and more advanced. This kind of rain sensor features small size, high sensitivity, intelligence, sound stability, and easy maintenance. Rainfall sensors can be adopted in such departments as meteorological stations, hydrological stations, agriculture and forestry, national defense, field observation and reporting stations, and so on, so that raw data can be provided for flood prevention, water supply dispatching, and water management in power stations and reservoirs.

Figure 6.8 illustrates a dump bucket rain sensor, which is mainly composed of a rain receiving bucket, a metering bucket, a counting bucket, a throttle tube, a pulse generating circuit, a base, a magnetic steel, a reed pipe, and a casing. The tipping bucket rainfall sensor is used in meteorological stations, hydrological stations, agriculture, forestry, national defense, and other related departments for the measurement of liquid precipitation, precipitation intensity, and time of precipitation.

Fig. 6.7 Rainfall sensor

Fig. 6.8 The dump bucket rain sensor

Meanwhile, it can also be used to provide raw data for flood control, water supply dispatching, and water management of power stations and reservoirs.

The rainwater, collected by the water inlet of the bucket rainfall sensor, passes through the upper cylinder filter screen and is then injected into the metering bucket (Jiang et al. 2019). Injection-molded with engineering plastic, the bucket is divided into two equal-volume triangular buckets with an intermediate partition. Such a structure is mechanically bi-stable – one bucket receives water, while the other bucket waits. When the volume of rainwater received reaches a predetermined value, it falls over due to gravity and starts to wait, and the other bucket chamber starts to function. When the predetermined value is again reached, it too overturns and starts to wait. A magnetic steel, installed on the side wall of the dump bucket, scans from the side of the dry reed pipe as the bucket turns, so as to turn the dry reed pipe either on or off, which is to say that each time the tipping bucket is turned over, the dry reed switch is turned on and a switch signal is sent out. In this way, the number of times the tipping bucket is turned on and off is recorded by the pulse signal sent out by dry reed pipe, which is scanned via the magnetic steel. Each pulse signal recorded represents a certain amount of precipitation, thus achieving the purpose of remote precipitation detection. Refer to Fig. 6.9 for the structural schematic diagram of dump bucket rain sensor.

6.4.3 Evaporation Sensors

The purpose of water surface evaporation observation is to explore the distribution law of water surface evaporation in different regions and at different time points, so that the basis for hydrological calculation and scientific research can be provided.

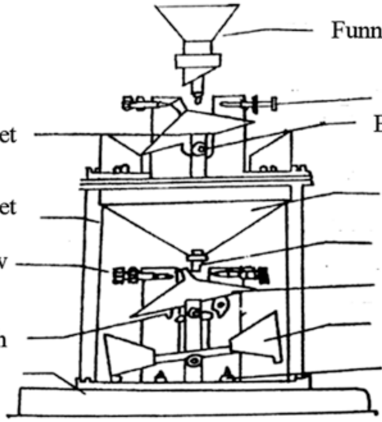

Fig. 6.9 Schematic diagram of dump bucket rain sensor

As information technology matures, the manual observation evaporators are replaced by digital and ultrasonic water surface evaporators, which can achieve automatic overflow, automatic water replenishment, automatic rainfall deduction, and automatic error correction, making the evaporation data more accurate, objective, and real-time.

6.4.3.1 Digital Evaporation Sensors

FFZ-01 digital water surface evaporation sensor, an instrument used to observe the change of water surface evaporation at different time periods, is manufactured in accordance with the requirements of the Ministry of Water Resources and Electric Power Standard *Water Surface Evaporation Observation Code* SD265-88, as shown in Fig. 6.10. The instrument can be directly applied, together with a Φ618mm evaporation bucket or with a 20 m^2 standard evaporation pond, to monitor the evaporation of water. Additionally, the instrument can be combined with evaporation data recorder to form a digital recording evaporator, which can automatically record the evaporation process. It can also be matched with JFZ-01 digital rain gauge and digital flow meter of overflow to form a fully automatic evaporation rain measurement station that is equipped with a basic evaporation network for automatic observation, recording, and remote transmission of evaporation and rainfall processes. The measurement accuracy and stability of the instrument are far superior to ultrasonic and other types of surface evaporation sensors. Moreover, it allows real-time remote transmission and is applicable to evaporation stations and weather stations across regions and types. Its primary features include:

- Free from drifts of temperature and time and stable over the long term.
- High resolution and high accuracy.

Fig. 6.10 The digital evaporation sensor

- Able to be observed normally under wind, wave, and rainfall climate conditions without loss of accuracy.
- Anti-electromagnetic interference – the data produced would remain correct even if the power is turned off and then on again.
- Able to be used in combination with evaporation bucket, hydrosphere, automatic water adding device, and recording device for the automatic monitoring of evaporation process.

Its scope of application is as follows:

- Real-time detection of evaporation data. Taking Yuan'an Station as an example, the computer transmits data from time to time every day, so that the automatic evaporation data is stored in the computer's local database. The evaporation transmission serial port is connected to the computer serial port via a converter, which allows the use of automatic evaporation monitoring software for low-level real-time information monitoring. The software displays the evaporation data of the day, the previous day, and the day before that, as well as the day's evaporation situation, evaporation water level, overflow water level, and other information.
- Evaporation data storage management. Click Evaporation Data Management in the abovementioned software, and the evaporation data is then automatically stored in the database set by the machine. The function of data management is to analyze and process the evaporation data and generate various reports as required.

6.4.3.2 Ultrasonic Evaporation Sensors

The ultrasonic evaporation sensor, adopting a top-loading structure, reduces the number of connection bolts of the valve body under conditions of high pressure and large diameter, thus enhancing the reliability of the valve and eliminating the influence of the system's own weight on the normal operation of the valve. In order to achieve automatic observation of evaporation, the meteorological department began to adopt the AG1.0 evaporation sensor based on E601B evaporator at the reference climate station from January 2003. Apart from their relative accuracy and stability, the sensors have also demonstrated low failure rate since they were put into operation. However, they are prone to wild values under severe weather conditions, such as strong wind and rain. In order to minimize the environmental impact on the measurement results, Zhonghuan Tianyi (Tianjin) Meteorological Instrument Co., Ltd. has developed the AG2.0 evaporation sensor, which modifies the installation method of the original AG1.0 sensor and improves the measurement accuracy by optimizing the application environment. The AG1.0 and AG2.0 ultrasonic evaporation sensors, operating at a frequency of 40 kHz, consist of an ultrasonic generator and a stainless steel cylinder. Including a transmitting probe and a receiving probe, the ultrasonic generator generates ultrasonic waves and automatically receives echoes. The transmitting probe converts high-frequency electrical vibration into high-frequency mechanical vibration to generate ultrasonic waves, while the receiving probe converts ultrasonic vibration waves into electrical signals. The signal detection system calculates the distance between the emission point and the water surface by measuring the time interval between the ultrasonic emission and the reflection after the water surface reflection. To determine the amount of evaporation, a relative quantity, during a given period, data on the water surface height only need to be acquired twice within that time for arithmetic calculations.

With respect to the application of ultrasonic evaporation sensor, the measurement accuracy of the sensor is subject to the measurement environment. When using the AG1.0 evaporation sensor directly above the E601B evaporator, the water surface humidity and air temperature significantly fluctuate, thus reducing the measurement accuracy. At the same time, the casing of the ultrasonic generator is easily deformed owing to long-term exposure to sunlight, resulting in zero offset. Under this installation method, the water surface is prone to fluctuations, and abnormal values tend to occur under severe weather conditions. AG2.0 ultrasonic evaporation sensor changes the original installation method (Wang et al. 2019). As shown in

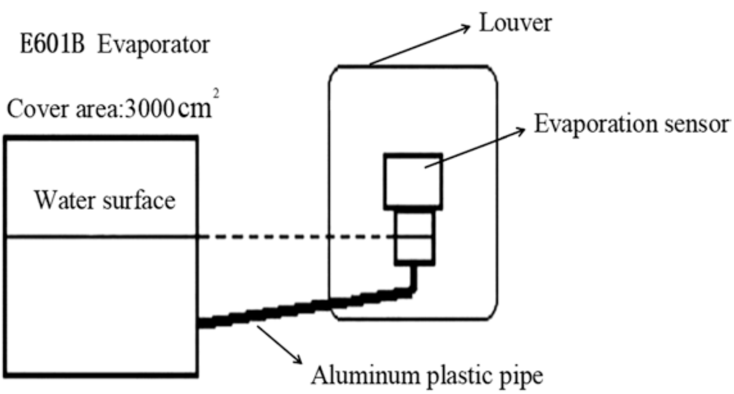

Fig. 6.11 Schematic diagram of AG2.0 ultrasonic evaporation sensor installation

Fig. 6.11, the ultrasonic evaporation sensor is installed outside the E601B evaporator and fixed in the louver. This reduces the influence of temperature and humidity on the accuracy of the measurement and also avoids abnormal values of liquid-level fluctuations under severe weather conditions. The evaporation sensor is connected to the evaporator through an aluminum-plastic tube. Under the effect of pressure balance, the height of the stainless steel cylinder of the evaporation sensor is the same as the water level of the evaporator.

6.4.4 Irradiation (Radiation) Sensors

Radiation sensors are divided into infrared sensors and nuclear radiation sensors. Nuclear radiation sensors are based on the absorption, backscattering of the measured substance, or the ionization excitation effect of the measured substance; hence, they are also referred to as radioisotope sensors. As a kind of sensor that uses infrared to process data, infrared sensors boast high sensitivity and can be used to control the operation of the driving device.

6.4.4.1 Infrared Sensor

Adopting the physical properties of infrared for measurement, infrared sensors share the same properties with visible light in terms of reflection, refraction, interference diffraction, and absorption. In the field of engineering, the areas occupied by infrared spectrum are divided into four regions: near-infrared region, mid-infrared region, far-infrared region, and extreme far-infrared region. Research in this regard found that the thermal effect of various monochromatic light in the solar spectrum gradually increases from purple to red and the maximum thermal effect should appear in the frequency range of infrared radiation.

Infrared sensors tap into the generation of infrared radiation by objects for automatic detection and include three parts: optical system, detection element, and conversion circuit. When infrared sensors are used for measurement, fast measurement speed and high sensitivity can be achieved. Additionally, infrared sensors engage in measurement without directly contacting the measured object. Infrared sensors can be divided into five categories depending on functions (Bai 2017), including:

- Radiometers for radiation and spectrum measurement
- A search and tracking system for exploring and tracking infrared targets that determines their spatial location and tracks their movements
- A thermal imaging system that produces an image of the entire target's infrared radiation distribution
- Infrared ranging and communication system
- Thermal imaging system with two or more combinations of various systems
- The application scope of infrared sensors:

- Night vision technology. The camera is equipped with an infrared sensor to achieve night vision, i.e., under night vision, the digital video camera will emit infrared light, invisible to the naked eye, to illuminate the object being shot. Turn off the infrared filter; and the infrared rays would no longer be blocked from entering the CCD and would be reflected by the object and enter the lens for imaging.
- Infrared detector. The core of the infrared system is an infrared detector, which can be divided into two categories according to the detection mechanism: thermal detectors and photon detectors.
- Non-destructive infrared. Non-destructive infrared flaw detectors can be used to inspect the internal defects of the component and any damage to the component structure.
- Infrared gas analyzer – using infrared gas for gas analysis. A signal of electrical detector is generated based on the different concentrations of the component, the different absorbed radiant energies, the different rises of temperature in the detector for the remaining radiant energy, and the different pressures borne by the two sides of the east thin membrane. In this way, the concentration of the component to be analyzed can be measured indirectly.

6.4.4.2 Nuclear Radiation Sensors

Nuclear radiation sensors include a radiation source, a detector, and a signal conversion circuit. The radiation source is generally disc-shaped (β-radiation source) or filament-shaped, cylindrical, or disc-shaped (γ-radiation source). For example, TI204 is plated on a copper sheet, covered with a mica sheet, then packed in an aluminum or stainless steel case, and finally sealed with epoxy resin, which becomes a radiation source. Detectors, also called receivers, are devices that detect the presence and strength of rays through the interaction of rays and matter. The functioning of detectors are generally based on the emission of certain substances under the influence of nuclear radiation or the effect of gas ionization. Commonly used detectors include current ionization chamber, Geiger counting tube, and scintillation counting tube. In terms of the working principle of nuclear radiation sensors, the functioning of these sensors is based on the absorption, backscattering of the measured substance, or the ionization excitation of the measured substance by the radiation. Nuclear radiation measurement is mainly used in tomography (industrial CT, medical CT), non-destructive testing, pre-furnace analysis, on-site element analysis, online monitoring, environmental monitoring, flaw detection, and so on. Zero radioisotopes emit particles (rays) with a certain energy during the decay process, including alpha particles, beta particles, gamma rays, and neutron rays. Using alpha particles to ionize a gas is much stronger than using other radiation, which is why alpha particles are frequently used for gas composition analysis to measure the pressure, flow, or other parameters of a gas. Beta particles have a range of up to 20 meters in the gas. According to the material's absorption of beta radiation, the thickness and density of the material can be measured; the thickness of the cover layer can be judged by looking at the reflection of the beta radiation; and the gas flow rate can be determined using ionizing capacity of the beta particles. As a kind of electromagnetic radiation, γ-ray has a strong penetrating capability in matter and a range of hundreds of meters in gas. It is noteworthy that γ-ray can penetrate tens of centimeters into solid matter. This is the reason why γ-ray is widely used in metal inspection and thickness measurement, as well as the measurement of flow rate, level, and density. Neutron rays are often used to measure humidity, level, or composition of hydrogen-containing media. The scope of application of nuclear radiation sensors is as follows:

- Detection of parameters that include thickness, liquid level, material level, speed, material density, weight, gas pressure, flow rate, temperature, and humidity.
- Flaw detection of metal materials.
- Extensive application in pharmaceutical factories, laboratories, power plants, quarries, emergency rescue stations, metal processing plants, underground oil fields and oil pipeline equipment, environmental protection, and other departments. In the abovementioned scenarios, nuclear radiation sensors are used to check local radiation leakage and nuclear radiation pollution, the radon radiation cesium pollution of the surrounding environment, the cobalt 60 radiation pollution, the radioactivity of building materials such as stone, and the landfills and dumps where there is a danger of nuclear radiation. They are also adopted to test X-ray instruments for medical and industrial X-ray radiation intensity, radium pollution of groundwater, radioactivity monitoring of underground drill pipes and equipment used to measure air and water pollution around nuclear reactors, harmful radiation of personal valuables and jewelry, and radioactivity of porcelain tableware glass.

In order to make comprehensive agricultural bases more information-based and more intelligent, and to improve farming productivity and efficiency, a team designed the software and hardware structure of the front-end information collection system and back-end intelligent control system for agricultural IoT and developed the IoT information collection equipment and smart controlling equipment. The front-end information collection is combined with sensor nodes, wireless transmission network, and sensor configuration for information collection, while the back-end intelligent control system is combined with expert-linked systems, agricultural intelligent variable frequency irrigation systems, automatic greenhouse control systems, and so on to achieve smart control. The systems and instruments that were developed have yielded sound results in practical application and brought economic and ecological benefits and are key to the intelligent and information-based development of modern agriculture (Fig. 6.12).

Fig. 6.12 Effect of intelligent greenhouse control system

6.5 Summary

In this chapter, sensors of farmland conditions were introduced to analyze their working principle and application method in detail. The temperature and humidity of the soil and the composition of fertilizers ought to adapt to the needs of crop growth, and in order to facilitate such adjustments, sensors are needed for the detection and data processing of temperature, humidity, light intensity, carbon dioxide concentration, and other parameters in the environment. Thanks to these sensors with different functions, the efficient acquisition of farmland environmental information is made possible in agricultural IoT, thus facilitating the full use of farmland information in promoting agricultural development.

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Chapter 7
Livestock and Aquaculture Information Sensing Technology

Pengcheng Nie, Yong He, Fei Liu, and Hui Zhang

Abstract Livestock and aquaculture farming are prominent components of agriculture, and the development of modern animal husbandry and aquaculture is of great significance across the globe. The adoption of IoT-connected sensing, communication, and control technologies can modernize livestock, poultry, and aquaculture farming, while sensing technology and control methods can reduce production costs and improve farm risk resistance capability and product quality standards. An introduction of these technologies is laid out in this chapter.

Keywords Intelligent animal husbandry · Intelligent aquaculture · Sensing technology · Intelligent breeding · Welfare breeding

7.1 Introduction

Livestock and aquaculture farming, essential to China's agricultural and pastoral economy, are major agricultural products with regard to foreign exchange. In the past 20 years, growth rate of the total global aquatic output has been low, whereas that of China has grown rapidly. China's total output of aquatic products, currently accounting for approximately 35% of the global export, has been ranking first globally since 1990. According to statistics released by the International Meat Secretariat, China's total livestock and poultry production accounts for approximately 29% of the world's total production, ranking first in the world for 21 consecutive years. Among them, pork accounts for 47%, and mutton takes up 28%, ranking first globally in terms of production volume. It is safe to say that livestock and aquaculture farming has been critical to China's agro-economic development and rural construction.

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However, traditional farming methods have generated negative ramifications that are primarily manifested in the following aspects:

- It is difficult to guarantee the quality of products produced through experience-based aquaculture, and product quality standards are difficult to control.
- Traditional farming methods are costly with regard to labor and material resources. As labor costs rise, the cost of traditional farming has risen sharply.
- Traditional farming, based on the experience and judgment of breeders, lacks science-based diagnostic measures. Breeders are unable to render accurate diagnosis of livestock and aquaculture, exposing them to potential risks.

Therefore, modern livestock and aquaculture industry has been built. The adoption of sensor information technology, network communication technology, and automation control technology facilitates modern livestock and aquaculture farming, reduces production costs relying on information technology and control methods, enhances the resistance to risk, and improves the quality standards of products. Such adoptions are inevitable for the future development of livestock and aquaculture farming.

7.2 Sensing Technology for Livestock and Poultry Farming

7.2.1 Background Information on Livestock and Poultry Farming

Since the 1990s, thanks to the continuous emergence of new agricultural production technologies and the continuous adjustment of agricultural production structure, livestock farming in China has grown rapidly. The growth rate of pig farming was particularly fast, manifested by the expansion of farming scale and rapid growth in number, rendering major contributions to optimizing the rural economic structure, improving agricultural benefits, and increasing farmers' income (Tai et al. 2012).

However, as livestock farming continues to grow in scale and further intensifies, a number of epidemic diseases have also broke out, imposing huge tolls on the industry and threatening the lives and health of human beings. Against such a backdrop, intelligent farming technology that can improve livestock quality and increase related exports has been drawing increasing public attention (Neethirajan et al. 2017; Wang et al. 2018a).

Through continuous development, modern livestock farming has become a "high-input, high-output and high-efficiency" industry that is capital-intensive and labor-intensive. However, livestock farming in China is less automated and way more labor-intensive than developed countries. Recent years saw the continuous development of China's economy; as a result, livestock farming has gradually transitioned to become capital-intensive. However, such capital-intensive production method also brings heavy consumption of resources and labor and a certain impact

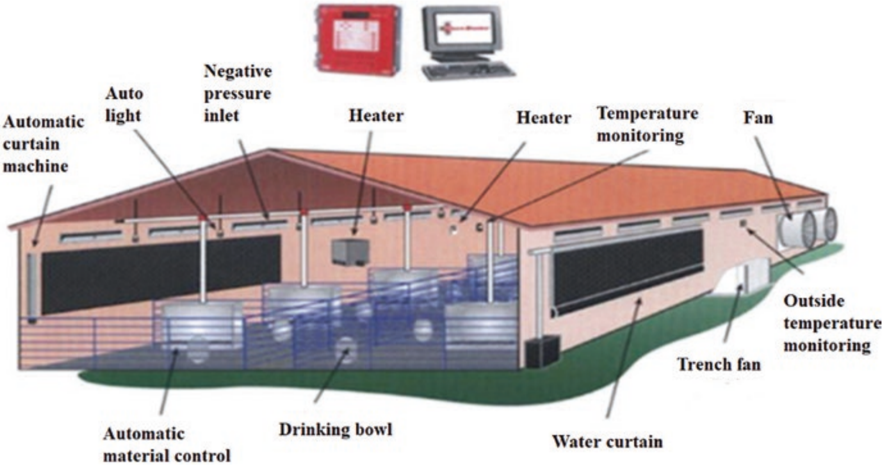

Fig. 7.1 Intelligent livestock farming base

on the environment. Adopting IoT technology, the consumption of resources can be reduced. The technology can be used to reduce the environmental pollution of traditional aquaculture and transform modern livestock farming into a resource-saving, environmentally friendly, properly managed, and efficient green industry (Bryukhanov et al. 2019; Qun et al. 2019; Ren et al. 2020).

Modern livestock farming IoT is achieved through the application of advanced sensing technology, multidimensional information sensing technology, and intelligent information processing technology. Livestock trajectory monitoring, animal physiological information feedback, and real-time monitoring of farming environment information are made possible relying on advanced sensing technology. The remote monitoring network is established through the application of multidimensional and self-organizing information transmission technology. As is shown in Fig. 7.1, using intelligent information processing technology, the independent management of the entire life cycle of animals is realized.

7.2.2 *Information Needed for Livestock and Poultry Systems*

Intelligent livestock and poultry breeding system widely uses a variety of integrated, miniaturized, high reliability, low power consumption, low cost sensor technology, such as RFID electronic label wireless technology, WSN wireless communications technology, 3G wireless remote communication technology, intelligent cloud computing technology, estrus automatic monitoring technology, breeding prediction technology, nutrition model dynamic detection technology, automatic control technology, etc. An intelligent system for healthy farming of livestock has been built, which integrated farming environment monitoring, individual identification of livestock and poultry, intelligent sensing of individual information, acquisition of animal farming information, data collection and conversion, intelligent data transmission (wired or wireless), intelligent analysis and processing of data, disease diagnosis and early warning, and livestock precision feeding. It achieved the full application of IoT technology (Yan and Shi 2014). The application of all the IoT technologies constitutes the main application systems in modern livestock farming, thus giving birth to the livestock farming IoT system.

7.2.2.1 Environmental Monitoring System

During the growth process, livestock is connected with the environment and affect each other in various ways. In modern livestock farming, the impact of the environment on livestock is gradually recognized and valued. There are four main factors in the production process of livestock: breed, feed, epidemic prevention, and environment. First of all, a quality breed of the livestock is required. On this basis, in order to fully realize the growth potential of excellent varieties, it is also necessary to have high-quality feed and keep good health. In addition, a comfortable environment for livestock growth must be provided. Feed utilization would decrease if the environment is not suitable. If the livestock fails to eat properly, the immunity of the livestock will decrease, and the rate of morbidity and mortality will increase. As a result, the excellent breeds cannot fully realize their genetic potential, causing huge economic losses. In modern livestock farming, with the increase in scale, intensification, and the use of latest farming technologies, the resistance of livestock decreased, and the requirements for environmental conditions have become more demanding. Therefore, it is particularly important to create suitable environmental conditions for livestock.

Equipped with various IoT technologies, the livestock farming environment monitoring system monitors and controls the environmental parameters of livestock farming sites. The main monitoring information include air temperature and humidity, light intensity, air circulation, and other thermal environments for livestock and poultry farming. These parameters affect not only the body heat regulation of livestock but also the body heat regulation through joint action. Harmful gases, such as CO_2, NH_3, CH_4, and H_2S, exist in the air. These harmful gases exert adverse effects on the growth of livestock, the balance of the environment, and the efficiency and health of workers. Generally speaking, these harmful gases are produced by the feces of livestock, decomposition of grass, respiration of livestock, and excessive feed.

The environmental monitoring system includes three main modules:

- Information acquisition module: automatically detecting, sending, and receiving temperature and humidity, light, CO_2, H_2S, ammonia nitrogen, and other signals in livestock farming sites
- Intelligent control module: responsible for the remote automatic control of the environment of livestock houses

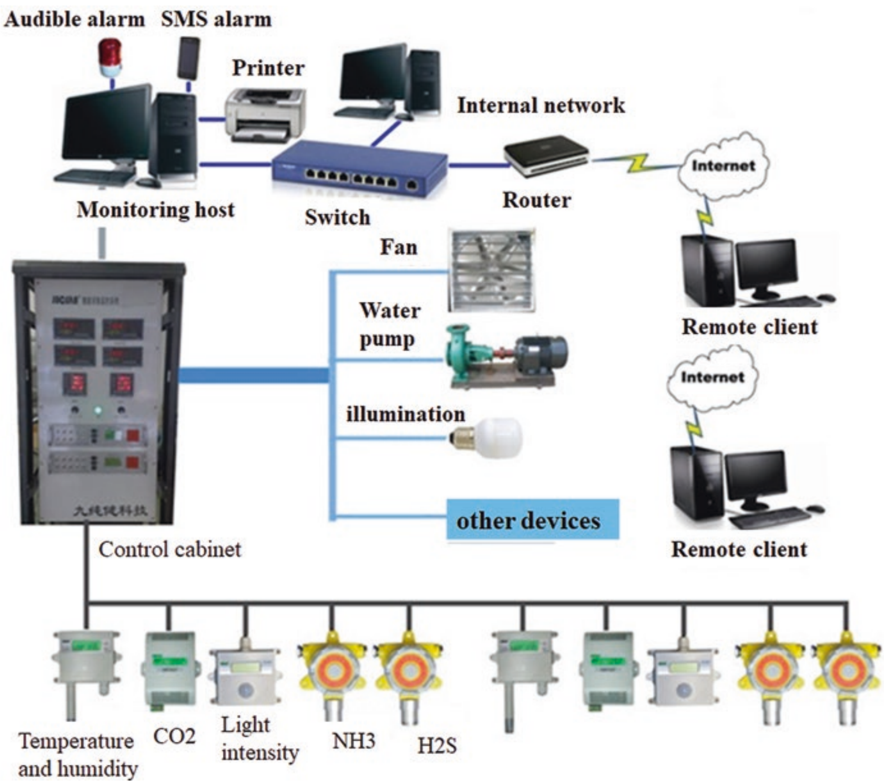

Fig. 7.2 Structure of environmental monitoring system (*Disclaimer*: Commercial products are referred to solely for the purpose of clarification and should not be construed as being endorsed by the authors or the institution with which the authors are affiliated)

- Management platform module: responsible for the storage, analysis, and management of signal data, setting environmental thresholds and intelligent analysis and early warning

  The system structure is shown in Fig. 7.2.

7.2.2.2 Fecal Treatment Sensing System

The system includes three parts: information collection module, stool collection module, and air purification module. Using temperature and humidity sensors, ammonia sensors, hydrogen sulfide sensors, and so on, the information collection module collects environmental information from livestock farming sites. Manure collection device can automatically or manually complete the collection of manure during livestock farming. When the information sensing module finds that the harmful gases such as methane, ammonia, and hydrogen sulfide in the livestock farm exceed the standard, the air purification module automatically adopts measures that include ventilation and air exchange.

7.2.2.3 Full Life Cycle Quality Traceability System

According to the requirements of the quality supervision department on healthy farming of livestock and quality of meat, the quality traceability system for the full life cycle of healthy farming of livestock is constructed, so that the entire process of individual livestock information can be traceable. A wearable ear chip, implanted with an electronic chip that can read and write data remotely, as well as store other biological information about the animal such as parents and even grandparents of the livestock, is placed on one of the ears on the animal. Besides, it can also store physiological information of individual growth periods of livestock, including dietary meals during each growth period, disease and diagnosis records, vaccination information, farming information, female bird pregnancy and fertility records, information on slaughtering, warehousing, transportation, and sales after listing. The quality tracing system allows the forward tracking of the full life cycle information of livestock, as well as the reverse tracing from meat retail terminal to farming information.

7.2.2.4 Precision Feeding System

As living standards improve, the demand on the quality of meat products is increasing, and the competition in livestock farming is becoming increasingly cut-throat. The traditional decentralized farming model has not been able to meet the needs of society. Gradually, large-scale farming has become the inevitable trend of livestock farming, and the feeding methods of livestock have also become automated and refined. The digital livestock precision feeding system integrates advanced sensing technology, computer technology, database management technology, automation technology, and information transmission technology. The system automatically determines the amount of feed to be deterred based on factors including breeds, frequency of activity, temperature and humidity, growth stage, and microclimates. In addition, real-time dynamics of the growth status and physiological indicators of livestock are predicted depending on feeding and monitoring information, so that refined feeding can be achieved. The main components of the system are as follows.

7.2.3 Sensing Technology for Livestock and Poultry Farming

The application of sensors in automatic feeding stations involves a number of aspects, including the measurement of ambient temperature and humidity and the collection and processing of physiological signals of livestock.

7.2.3.1 Ambient Temperature and Humidity Sensors

The temperature and humidity sensors are made of a high-precision digital sensor probe and an intelligent digital processing chip. The sensor collects temperature and humidity information in the environment and converts it into an electrical signal, which can be displayed as temperature and humidity data when processed by the processing chip. Temperature and humidity sensors can be associated with the central control system for data collection (below is an illustration of temperature and humidity sensor). The sensor, combining temperature and humidity measurements, features small size, fast and accurate measurement, convenient monitoring, and easy installation, thus making it applicable in automatic feeding stations.

7.2.3.2 Physiological Information Sensors

The physiological information of livestock is primarily collected by the implanted physiological signal chip. The sensor relies on the implanted signal acquisition method to handle the information collected by the physiological signal sensing chip attached to the livestock through advanced wireless technology. It then passes the data to the intelligent processor, which uses modern intelligent algorithms to analyze and process the signals to obtain various physiological indicators that reflect health status. The system can be counted on to monitor physiological parameters, such as temperature and blood pressure of awake and unrestrained animals, in real time. It is noteworthy that this system does not require anesthesia or restraint of individual livestock. While ensuring the free movement of animals, it measures various physiological indicators that can best reflect the growth conditions of animals under normal conditions, thus meeting all the needs of breeders.

The implantable physiological signal chip has two working modes, individual measurement of livestock and simultaneous measurement of multiple individuals, which can be selected according to different needs. The latter of which, based on the individual measurement of livestock, is upgraded to a multichannel mode via the data processing chip, thereby achieving simultaneous measurement of multiple individuals.

7.2.3.3 Body Temperature Sensors

The temperature measurement of livestock represents a key link of sensor application in the automatic fine feeding system, which is why the selection of measuring instruments is critical. The animal infrared thermometer collects the radiant energy in the infrared radiation emitted by the individual livestock and converts it into an electrical signal. Since the radiated energy is positively correlated with the transformed electrical signal, the body temperature of livestock and poultry can be obtained through a certain transformation relationship. In addition, the actual body temperature of livestock is corrected by measuring the surface temperature of the animal. The accuracy of temperature measurement is high and the speed is fast. It features digital display, data recording, and alarm auto-sleeping, functions that are suited for measuring the temperature of livestock in large-scale farming.

7.2.4 Applications

7.2.4.1 Automatic Performance Measurement System of Boars

Automatic performance measurement system of boars (feed intake recording equipment, FIRE) is an automated, intelligent feed ration system that continuously accurately records feed intake in large-scale farming. The system consists of multiple measuring stations; each is connected by a 4-core cable and linked to a computer. Each measuring station is equipped with an IFC (functional controller) and relevant equipment that include equipment used to identify electronic ear tags for boars and equipment used to weigh and feed the trough. An adjustable width fence, installed in front of the trough, grants access to only one pig per feeding. Individual weight scales are also installed in front of the trough for the simultaneous measurement of the animal's weight.

The FIRE system relies on a passive method for measurement recording, which means that the system carries out measurement without the need to enter pig numbers, and all that is required is to tag the pigs with electronic ear tags and let them enter the trough for feed.

When the pigs are fed, the system records the data through feeding activities. The IFC records the electronic ear tags of pigs at each feeding, starting and ending time of feeding, and consumption while measuring their weight. If no pig ear tag is detected after feeding, the feed intake data will be recorded in the Zero Ear Tag database, which is referred to as the "Zero Ear Tag" event in the system manual and software. The measurement records can be maintained for several days (the number of days is determined by the type of FIRE measurement station and the feeding behavior of the pigs). If the measurement data is not transferred from the IFC to the computer before the IFC memory is full, the new measurement record will overwrite the old ones.

The FIRE software, running in the computer, controls the operation of the FIRE system and contains a database of daily records for each pig measured. Once the measurement station transmits the event data to the computer, the database records in the station are automatically updated. Individual or group records can be displayed or printed through a series of comprehensive reports, and the diagnostic program helps the user monitor the operating status of the FIRE system. Figure 7.3 shows an overall configuration of the FIRE system.

Hopper, the most basic component of the FIRE system, consists of components that record and store feed intake and weighing. The trough connection fence allows only one pig to enter per time.

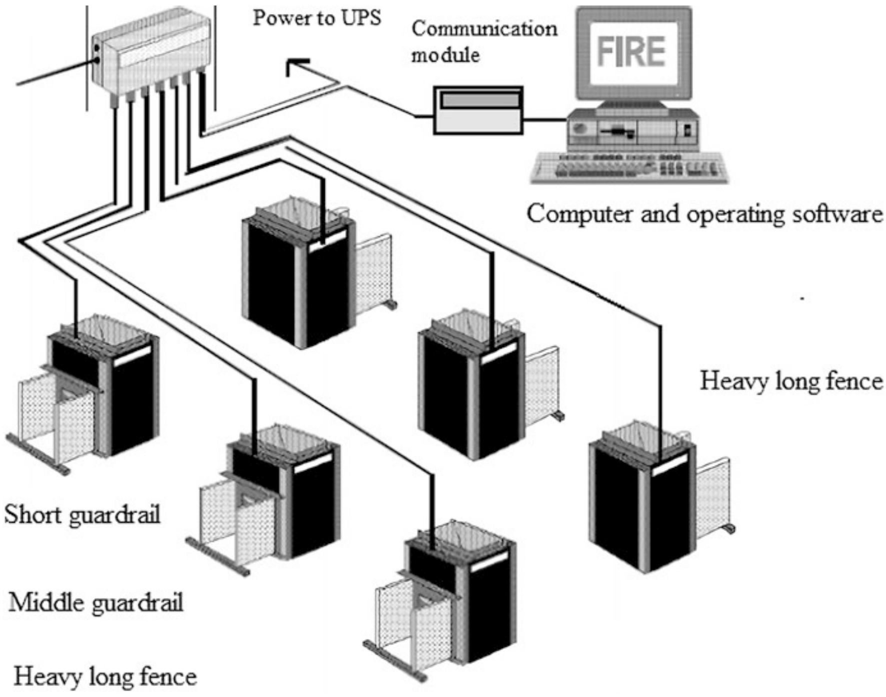

Fig. 7.3 System configuration diagram

The width of the guardrail, connected to the measuring tank, is adjustable, and only one pig is allowed to enter each time. Guardrails can be divided into several types. For instance, shoulder guardrails come with adjustable width, and their length is extended behind the shoulders of the pigs that are prepared to eat, allowing appropriate levels of competition among pigs. The shoulder fence, connected to the FIRE measurement station, covers the head and shoulders of the pigs that are eating, allowing for moderate competition. The shoulder rail is approximately 35 cm in length, and as test pig grows, the shoulder fence can be widened to accommodate the test pig. It is advisable to adjust the width by about 4 cm beyond the width of the pig to be measured. With regard to long guardrail that also features adjustable width, the length reaches the whole body of the pig, providing comprehensive protection for the pig (refer to Fig. 7.4 for an illustration of the long guardrail). The long guardrail is connected to the FIRE station, covering the whole body of the pigs, thus restricting competition. The length of the whole fence is about 91 cm. Similarly, the long fence can also be widened to match the growth of pigs. It is advisable to adjust the width by about 4 cm beyond the width of the pig to be measured.

The width of weighing guardrails is also adjustable, and their length reaches the whole body of the pig. When the pigs are eating, they stand on the weighing scale and are weighed. Figure 7.5 is an illustration of a weighing guardrail.

Fig. 7.4 Long guardrail

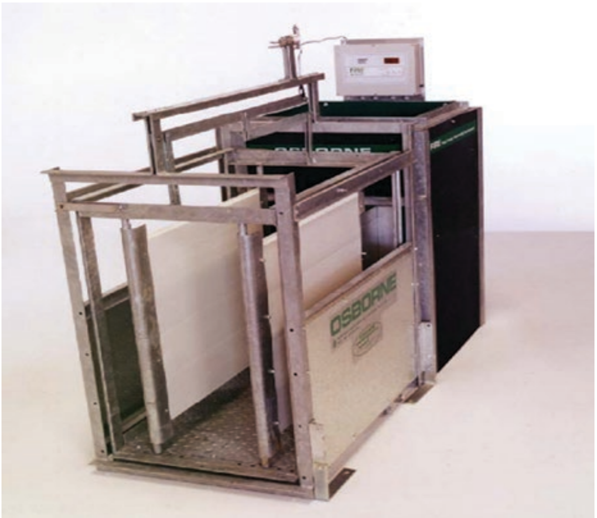

Fig. 7.5 Weighing guardrail

The long guardrail is located in front of the FIRE measurement station, providing full-body cover for the pigs, limiting competition. In addition to providing feeding protection for the test pigs, the guardrails also allow them to be continuously weighed. This interference-free weighing method is the most effective way to determine growth rate. The length of the weighing fence is about 91 cm, and as the pig grows, the fence can be widened to make accommodations. When the pig enters for feed, the weight scale will periodically check its weight and store the data in the FIRE measurement station. The measurement station engages in a permutation processing based on these weight data, takes the median value as the weight of the current measurement pig, and records into the feeding event data. In this way, by measuring feed intake multiple times a day, reliable daily weight records can be obtained. Due to animal behaviors, the weight of a certain pig may not be accurate in a given measurement; however the results of repeated weighing can be said to be reliable.

The weight of the trough is monitored whether the animal is feeding or not. When the pig enters the measuring station, the identification number of the measuring pig will be detected. Meanwhile, the system will generate an event or feeding record to represent the activity of the pig. While the pigs are eating, their weight is weighed as the basis for calculating the daily weight gain.

When the measuring station notices needs of replenishing feed in the trough (based on the minimum remaining feed in the trough set in the main computer), the batcher starts to function and replenishes the feed. Such replenishing may occur when the pigs are eating or not. If replenishing occurs while the pig is eating, the system uses the DPC value to correct the original trough weight when the feed is loaded. If not, this filling event will rely on data from most recent replenishing to automatically correct the DPC value.

When the pig leaves the measuring station (the identification number cannot be detected), the final weight of the feeding trough when the pig leaves is determined as the weight of the feeding trough, and the difference between the front and rear weights of the feeding trough equals the feeding amount. If the same pig re-enters the measuring station within 5 minutes, the two feeding activities will be combined into one.

If the feed is replenished when pigs are not eating, and when the feed in the supplementary feed tank does not exceed 50 g, the replenishing will be considered invalid, and another replenishing will be arranged. If the refilling is unsuccessful, the FIRE measuring station will issue a warning, indicating that the feed loading has failed. For this reason, the measuring station will not replenish feed within 1 hour or until the warning is removed. The warning can be cancelled by pressing the button in the measuring station, or through the host computer.

7.2.4.2 Velos Intelligent Sow Management System

In the Velos intelligent sow management system, each sow wears an electronic ear tag, which stores all the data concerning their entire life cycle. The amount of feed can be adjusted according to the growth status, activity, breed information, and even seasonal factors. The system recognizes electronic ear tags and controls the automatic feeding mechanism for accurate feeding according to the corresponding feeding curve. This approach avoids fluctuations in sow growth due to inaccurate feeding amounts, feed waste, and stress eating, ensuring that all sows receive the most accurate feed.

In addition, the system is equipped with an automatic separator, which separates sick sows, vaccinated sows, estrus sows, and farrowing sows into different areas and marks them in real time. Meanwhile, remote management technology can enable managers in different places to be informed promptly and bring about information-based and modern pig farm management. At present, the Velos intelligent sow management system is widely used, particularly in the Netherlands, a number of European countries, and the United States.

To achieve accurate and intelligent feeding in large-scale farming, it is necessary to be able to identify the individual identity of sows. Velos wears each sow with an electronic ear tag featuring RFID, which is the electronic "identity card" of sows (as shown in Fig. 7.6).

Velos sow feeding station aims at achieving precise feed control of the individual sows. In livestock farming plants, the cost of feed accounts for approximately 35% of the total costs, and the precise feeding of individual sows can help farming plant see their costs reduced. Additionally, physical conditions of sows can be controlled by adjusting the amount of feed. Therefore, automation of feeding delivers tangible benefits to farming plants. Refer to Fig. 7.7 for an illustration of the structure of the feeding station.

Adopting advanced sensing technology, image video processing technology, and data processing technology, the Velos estrus monitor enables real-time monitoring of sows and records the identity information of sows that visited boars and the time and duration of visit. Based on the frequency of visits and the time of communication with boars, the employees of the farming plant can render accurate judgment on

Fig. 7.6 Electronic ear tag

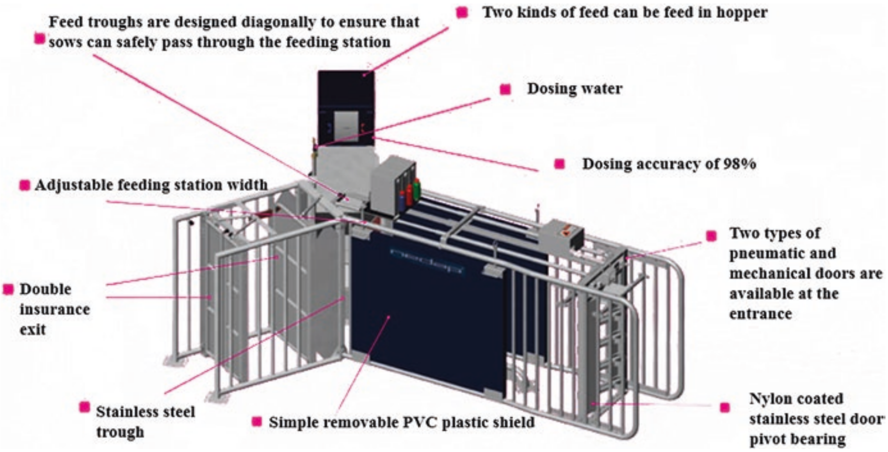

Fig. 7.7 Velos sow feeding station

whether the sow is in estrus and obtain the best breeding time, thereby improving the success rate and reproductive efficiency.

7.3 Sensing Technology for Aquaculture

7.3.1 Background Information on Aquaculture

As an important part of China's agricultural and pastoral economy, aquaculture has evolved into a major pillar industry in China's rural economy. In the past 20 years, China's aquatic production volume has maintained a sound growth momentum, whereas growth rate of the global aquatic production volume has been slow. Since 1990, China's total production volume output has been ranking first globally, occupying 73% of the global production and 35% of global export. Aquaculture plays an irreplaceable role in increasing farmers' income and improving their living standards. Therefore, maintaining the ecological balance of the aquaculture environment is particularly important for the high-speed and sustainable growth of aquaculture.

Traditional aquaculture models have significantly contributed to the rapid growth of aquatic production volume in China (Liu et al. 2012; Zhu et al. 2012). However, as living standards and green awareness continue to rise, people saw huge changes in their living habits and diet structure, and green and harmless aquatic products have become increasingly popular from among the general public. Due to various unfavorable factors in the traditional farming mode, the aquatic products produced cannot meet market needs, which is demonstrated in the following aspects.

7.3.1.1 Rough Production Facilities and Weak Economic Foundation

The traditional aquaculture model lacks the scaled management and the modern production technology necessary for large-scale and high-standard aquaculture production, resulting in a weak economic foundation and weak returns. The farming plant lacks technical support, the ability to transform, and the fund needed for scaling. Therefore, they can only manage to maintain the status quo and wait to be gradually replaced by modern aquaculture technology.

7.3.1.2 Environmental Conditions of Aquaculture Waters

Most of the waters in China's densely populated areas suffer from eutrophication. For example, among the more than 1200 rivers that are under water quality monitoring nationwide, 850 are polluted. In terms of oceans, large-scale and harmful red tides have occurred in China many times since the twenty-first century, causing huge economic losses to fishermen who rely on marine aquaculture. In the suburbs of large- and medium-sized cities, for various reasons, the pollution of aquaculture waters is becoming increasingly severe.

7.3.1.3 Secondary Pollution of Aquaculture Waters

With respect to marine aquaculture, due to the excessive growth of aquaculture, its sewage discharge has far exceeded the capacity of marine self-purification. A typical case is the continuous increase in shrimp disease. Regarding freshwater aquaculture, according to statistics from the statistics department, the manure produced by each ton of freshwater fish exceeds that of more than 20 fat pigs. Take the cage culture of an anonymous reservoir as an example; the average annual yield per mu (=0.0667 hectares) is about 20 tons, and the apparent economic benefits are relatively sound. However, this method of cultivation increased the active phosphate in the reservoir by 10.3 times, the amount of ammonia nitrogen grew by 7.3 times, and the quality of water and fertilization became worse, which is why cage fish farming must be stopped. At the same time, the subsequent cost of water quality improvement far outstrips the profit of cage culture.

7.3.1.4 Serious Damage to Aquatic Resources and Ecological Imbalance in Many Waters

The excessive growth of aquaculture has led to the destruction of aquatic grass, the increase of harmful aquatic organisms, the deterioration of the growth environment of the original excellent species, and the loss of nutrients, thus causing degradation and posing direct threats to the survival and growth of aquaculture. The intelligent aquaculture environment monitoring system, based on modern agricultural IoT, meets the demand of safe, intensive, high-yield, and efficient growth of aquaculture. The system makes integrated use of intelligent water information sensing, wireless reliable sensor network, intelligent information processing and control, and IoT technologies such as expert diagnostic systems. It has enabled the collection and intelligent control of water body and aquaculture information, meeting the high standards of intensive aquaculture and enabling the rapid and sustainable growth of aquaculture.

7.3.2 *Aquatic Information Sensing System*

As shown in Fig. 7.8, the aquatic information sensing system consists of an intelligent water quality sensor, a wireless sensor network, an aeration controller, and a monitoring platform.

Traditional water quality sensors are mostly based on electrochemical principles, and their measured values are susceptible to external factors that include flow rate, temperature, pressure, and so on. Additionally, their calibration is highly

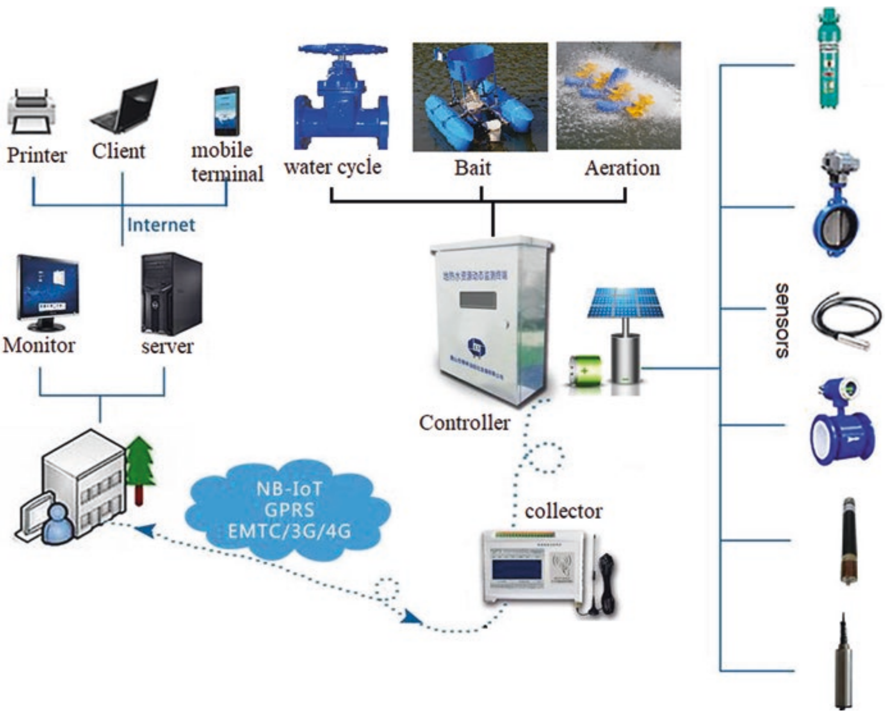

Fig. 7.8 Aquaculture information sensing system

complicated, their service life is short, and they cannot be used for long-term real-time monitoring. As technologies continue to improve, intelligent sensors have been created, which features self-calibration, self-identification, and so on. Intelligent sensors do not require manual intervention. They automatically collect data and preprocess the collected data. Furthermore, the sensors are also equipped with such functions as standardized digital output and two-way communication with the upper computer. According to the requirements on water quality of intensive aquaculture, intelligent water quality sensors monitor five parameters simultaneously, namely, temperature, turbidity, dissolved oxygen, electrical conductivity, and pH. The water quality sensor used is highly reliable and easy to maintain and is suitable for extensive application in aquaculture.

As the Chinese say, "aquaculture depends on quality water"; water is where aquatic organisms are born, live, and perish. The farming environment must not be a mere place for survival; it also bears the responsibility of cultivating natural food. The three factors of water quality change, fish culture density, and feed feeding amount are mutually restraint and interdependent, a relationship that determines the complexity and difficulty of water quality control.

Water quality holds the key to farming species, and the main indicators affecting water quality include turbidity, water temperature, pH values, dissolved oxygen, nitrite, ammonia nitrogen, and residual chlorine. According to the development standards of modern intensive fish farming, aquaculture water bodies must be regularly and comprehensively tested in order to determine, in real time, that the water quality meets the requirements of the breed. Another role of such testing is to evaluate water quality so as to provide the correct basis for rational medication and reduce the cost of farming (Hu et al. 2020; Zhang et al. 2020). Figure 7.9 demonstrates the application of various water quality sensors in aquaculture production bases.

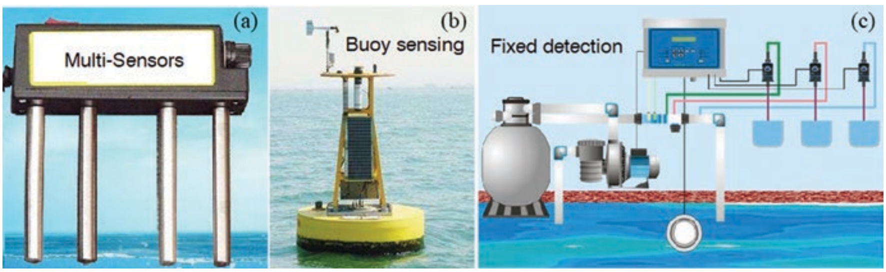

Fig. 7.9 Application of water quality detection sensor: (**a**) multi-sensors, (**b**) buoy sensing, (**c**) fixed detection

7.3.3 Aquaculture Water Quality Sensing Technology

7.3.3.1 Turbidity Sensors

Turbidity refers to the degree of obstruction caused by solution when light passes through. It includes the scattering of light by suspended matter and the absorption of light by solute molecules. Turbidity of water relates not only to the content of suspended matter in the water body but also to their size, shape, and refractive index.

Generally speaking, turbidity is not equivalent to the suspended solid concentration, which refers to the amount of substances that can be retained by filter paper in a unit of water, while turbidity is an optical effect that illustrates the degree of obstruction when light passes through the water layer. This optical effect is related to the size, shape, structure, and composition of the particles. There is an inherent relationship between turbidity and suspended solid concentration, but the correlation is quite complicated. Turbidity cannot be measured directly, and it describes colloids and suspended solids in liquids. Thus, turbidity is measured indirectly by the amount of transmitted or scattered light of a solution. The higher the turbidity of water, the stronger the reflected and scattered light, and conversely, the lower the turbidity of water, the weaker the reflected and scattered light.

The turbidity value is the result of the interaction among all the substances in the solution. Through standardized analysis methods, turbidity measurement can be used as a quantitative analysis for water quality monitoring. A standard turbidity unit is defined in water quality testing as turbidity consisting of 1 mg of SiO2 in 1 L of water, referred to as 1 degree. As a major indicator of the physical characteristics of water, turbidity reflects the degree of clarity or turbidity of water. There is a clear correlation between turbidity and microbial indicators in water. Because the surface of the particles absorbs nutrients, water with high turbidity will promote the growth and reproduction of bacteria, so that the attached bacteria grow and reproduce faster than free bacteria. At the same time, turbidity can reduce the effect of disinfectants on microorganisms and weaken the treatment effect on microorganisms, thereby increasing the chlorine and oxygen demands of water bodies.

As a measuring device for turbidity of water body, turbidimeter is divided into transmitted light type, scattered light type, and transmitted-scattered light type depending on the measuring principle. The general principle of the device is as follows: when light is irradiated into the water body, the ratio of the intensity of the incident light, the intensity of the transmitted light, and the intensity of the scattered light are related to the turbidity of the water body, which is determined by measuring the intensity of three kinds of light measuring. Optical turbidimeters are used for both research and on-spot automatic continuous measurement.

At present, the turbidity measurement methods are mainly divided into three types according to the light-receiving method: transmitted light turbidity measurement method, scattered light turbidity measurement method, and transmitted light-scattered light comparison measurement method.

7.3.3.2 Water Temperature Sensor

Water temperature regulation is critical to the management of aquatic production. On the one hand, water temperature represents a major parameter of water quality that exerts direct impact on the physiological behavior of fish. For instance, water temperature will directly affect the physiological and biochemical behaviors of aquatic organisms, including food intake, feed conversion rate, growth rate, survival rate, and spawning cycle. In addition, different types of aquatic organisms and even different individuals of the same type and different growth periods require different temperatures. Aquatic organisms are mostly temperature-varying animals, which means that their body temperature will change with water temperatures. Studies have shown that most fish can hardly survive when their body temperature is maintained at 35 °C for a long time; when their body temperature changes by 1 °C, the efficiency of many physiological processes in the body will change by 6~10%.

On the one hand, as water temperatures increase, the amount of dissolved oxygen in water significantly decreases, the respiration rate of fish accelerates, and oxygen consumption increases. Coupled with the combined effects of other aerobic organisms in the pond, hypoxia easily occurs in waters, which adversely affects fish. On the other hand, water temperature will bring indirect impact on other water quality parameters (such as PH, TAN, DO, TSS, etc.). Water temperatures also affect the toxicity of toxins, such as ammonia nitrogen, in ponds and the growth and reproduction rate of aerobic saprophytic bacteria and are closely related to the rate of various diseases.

All of the above makes water temperature a major sensing parameter in aquaculture. Operating costs increase as water temperature regulation comes with heightened energy consumption, and as such, the design of the water temperature control system is critical to aquaculture production, aquatic product quality, and total revenue.

Aquaculture water temperature regulation is aimed at providing suitable growth temperatures for the target species, which is why the quality of the water temperature regulation system significantly impacts the volume and quality of production. The principle of water temperature sensor is similar to the environmental temperature sensor based on the electrochemical principle, in that both are composed of thermal-sensitive materials that include thermal resistance or thermocouple.

7.3.3.3 Dissolved Oxygen Sensor

Dissolved oxygen (DO), a molecular oxygen in air that is dissolved in water, can be seen as the amount of oxygen dissolved in water and is expressed in milligrams of oxygen per liter of water. Apart from being an indicator for measuring the self-purification ability of water, the amount of dissolved oxygen in water also represents the most important water quality standard in pond farming and is indispensable to aquaculture farming.

In general, the amount of saturated dissolved oxygen in fresh water is only 1/20 of the oxygen content in air, and that contained in seawater is even less. If the amount of dissolved oxygen is too low, aquatic products will not be able to adapt, directly affecting their survival, production, growth, and digestion and also indirectly affecting the elimination of harmful substances in water quality and the decomposition of organic pollutants. Therefore, dissolved oxygen is one of the most concerned water quality factors in aquaculture.

The Role of Dissolved Oxygen in Aquaculture

Dissolved oxygen in water is a major factor for the survival and growth of fish and other food organisms. When the amount of dissolved oxygen in water fails to meet the fish's respiratory needs, i.e., below the critical oxygen depth, breathing is hindered, movement of breathing is strengthened, the frequency of breathing is accelerated, and fish frequently float to the surface for oxygen. When dissolved oxygen is below the range that fish can tolerate, suffocation may occur. According to the quality standard of aquaculture waters in China, dissolved oxygen must not fall below 5 mg/L for more than 16 hours a day and must not fall below 3 mg/L when the required 16 hours pass. Generally, the dissolved oxygen of warm-water fish should be above 5 mg/L, while the requirements of dissolved oxygen for cold-water fish such as salmon and trout are preferably saturated or close to saturation.

Dissolved oxygen provides the oxygen necessary for the growth of farmed fish. The oxygen ingested by animals through breathing ensures smooth energy conversion. In the event of insufficient oxygen, energy conversion terminates, and the fish face potential death. Furthermore, dissolved oxygen facilitates the growth and reproduction of aerobic microorganisms and accelerates the degradation of organic matter. Under aerobic conditions, aerobic microorganisms gradually degrade biological corpses, feces, baits, and other organic debris into various soluble organic substances through extracellular enzymes and finally become simple inorganic substances, enabling them to enter new material circulation and, in turn, reducing organic pollution in water bodies.

In addition, dissolved oxygen reduces toxic and harmful substances: oxygen relies on its strong oxidizing properties to directly degrade toxic and harmful substances, such as hydrogen sulfide and nitrite, in water and substrates, and oxidize them into sulfates, nitrates, and other toxic substances with low toxicity or even nontoxic substance.

Moreover, dissolved oxygen inhibits the activity of harmful anaerobic microorganisms. In anoxic water, anaerobic microorganisms grow and metabolize actively. Through the anaerobic fermentation of organic matter, a number of fermentation intermediates, such as hydrogen sulfide and methane, are produced, which makes water and substrate black and stinky and causes great harm to fish. However, when there is sufficient oxygen in water, anaerobic microorganisms are suppressed, which help create a suitable farming environment.

What is also noteworthy is that dissolved oxygen improves the immunity of aquaculture animals. Higher dissolved oxygen content helps increase the tolerance of fish to unfavorable environmental factors that include ammonia nitrogen and nitrite and enhances the tolerance to environmental stress. If a fish stays in water with insufficient dissolved oxygen, its immunity will gradually decrease, so would its resistance to pathogens, and the risk of infection will increase.

It can be seen that dissolved oxygen is one of the most important and problem-prone water quality factors in aquaculture. The amount of dissolved oxygen constantly fluctuates due to the combined effects of environmental temperature, biological activities, and other physical and chemical factors.

Dissolved oxygen content exerts significant impact on the reproduction of aquatic organisms, cultivation of seedlings and their feeding rate, feed utilization rate, and weight gain rate. During anoxia, ammonia nitrogen accumulates in water, and microorganisms play a leading role in the release of ammonia nitrogen in the sediment. Under anoxic and anaerobic conditions, ammonia nitrogen is produced in large quantities in the water sediment. The dissolved oxygen content in the sediment is quite low, and the release intensity of ammonia nitrogen increases with the decrease of oxygen.

Modern aquaculture is becoming more intensive, and yields are getting increasingly higher, thus increasing the importance of dissolved oxygen control in water. High-density aquaculture increases the oxygen consumption factor of water, and both its own oxygen production capacity and dissolved oxygen regulation capacity fail to meet the requirements of the aquaculture. In order to ensure the rapid development of aquaculture, it is essential to master the law of dissolved oxygen changes and take targeted regulatory measures to ensure the enhancement of aquaculture technology, thereby laying a solid foundation for improved aquaculture benefits and guaranteeing the healthy growth of farmed products.

Detection Mechanism of Dissolved Oxygen in Water

DO, the abbreviation of dissolved oxygen, refers to the concentration of molecular oxygen dissolved in water. The unit of dissolved oxygen is mg/L^{-1}, which means the number of milligrams of oxygen per liter of water.

The rapid and accurate monitoring of dissolved oxygen is of great significance in the fields of environmental monitoring, aquaculture, and biochemical treatment of wastewater. The solubility of oxygen in water is subject to the combination of water temperature, dissolved salts in water, total pressure, and partial pressure of water. The ability of water to dissolve oxygen is directly proportional to atmospheric pressure, which is evidenced by Henry's law and Dalton's law.

The measurement of dissolved oxygen is generally divided into chemical method and instrument method. Chemical methods are mainly titration and visual colorimetry, while instrumental methods include optical analysis, chromatographic analysis, and electrochemical analysis. Among these, electrochemical methods are further divided into polarographic method, potential method, electric capacity method, conductivity method, and diaphragm electrode method (sensor method). Among the many methods, currently the most widely used are the chemical iodine method, electrochemical probe method (electrode method), and optical dissolved oxygen analysis method (sensor method).

The traditional chemical method for determining the dissolved oxygen content in water is the iodometric method, which adopts reagents to carry out the redox reaction and then determines the content by titration. As the earliest method for detecting dissolved oxygen, this method yields highly accurate measurement results. It is the benchmark method for measuring dissolved oxygen in water and is often used to verify the accuracy of other detection methods.

The iodometric method is a pure chemical detection method that involves long and complicated processes. The detection requires the preparation of a variety of reagents, which cannot meet the requirements of continuous online measurement. Thus, it is no longer used in farming and is mostly used in laboratories. At the same time, easily oxidizable organic substances, such as tannin, humic acid, and lignin, will interfere measurement results. Oxidizable sulfides, such as thiourea sulfides, also consume oxygen and cause interference in a similar way with the respiratory system. When the measurement involves such substances, other methods should be adopted instead. The common dissolved oxygen measurement kit on the market is a rapid on-spot method for measuring dissolved oxygen in water based on chemical methods and judges the range of dissolved oxygen in water by visual color difference, making the product relatively practical. However, sensitivity of the kit is generally low, which means the measured data is not as reliable.

The principle of the optical dissolved oxygen analysis method is that when oxygen is in contact with a fluorescent substance, the intensity of the red fluorescence produced by it is reduced, and the time of the red light generation is also reduced. By measuring the intensity and time of the red light, the oxygen concentration can be calculated. The sensor is equipped with a blue light-emitting diode, a red light-emitting diode, and a photodetection tube. When the modulated blue light is excited on the fluorescent substance, it emits red light. Due to the sudden effect of oxygen molecules, the time and intensity of red light are inversely proportional to the concentration of oxygen molecules. A red light source synchronized with blue light is used as a reference, the phase difference between the excited red light and the reference red light is measured, and the internal calibration value is compared to calculate the concentration of oxygen molecules. After some processing, the dissolved oxygen value is produced. The adoption of the optical method for measuring dissolved oxygen produces sound results. It is the ideal method for detecting dissolved oxygen because it is least affected by aquatic water pollutants and various interference factors, with high measurement accuracy and low maintenance costs. Though the current price of sensors and other equipment is relatively high, it is believed with the gradual reduction of costs in the future, it too will be extensively adopted in aquaculture.

The diaphragm electrode is a current-type electrode covered by a breathable film. There are two types of practical membrane electrodes for dissolved oxygen: polarography and galvanic cell.

Galvanic cell dissolved oxygen electrodes are generally made of precious metals, such as platinum, gold, or silver. The cathode is usually made of silver and the anode is made of lead. The anode and the cathode are filled with electrolyte, and the electrode is separated from the liquid to be measured by a waterproof and gas-permeable membrane. In water, oxygen penetrates into the electrode through the gas-permeable membrane and is reduced on the cathode. It needs to obtain electrons from the external circuit, and at the same time, the lead anode is oxidized to release electrons to the external circuit. After the external circuit is switched on, a signal current is passed, which is proportional to the oxygen concentration. By measuring the signal current, the current oxygen concentration in water can be calculated. The breathability of the breathable membrane at different temperatures is different, so the temperature is detected simultaneously, and the difference in breathability of the breathable membrane at different temperatures is compensated by a specific algorithm to obtain the right oxygen concentration.

The polarographic dissolved oxygen electrode is composed of a gold electrode (cathode) and a silver electrode (anode) and a potassium chloride or potassium hydroxide electrolyte. Oxygen diffuses into the electrolyte through the membrane and forms a measurement loop with the gold and silver electrodes. When a polarized voltage of 0.6 ~ 0.8 V is applied to the DO electrode, oxygen diffuses through the membrane, and the cathode releases electrons. The anode then accepts electrons and generates a current. According to Faraday's law, the current flowing through the electrode of the dissolved oxygen analyzer is proportional to the partial pressure of oxygen, and a linear relationship exists between the current and the oxygen concentration when the temperature is constant. The electrode method has a high degree of automation and low error rate. Compared with the iodometric method, it features simple operation, quickness, and high efficiency. Reagents are not needed, and measurement results can be produced within a short period of time. At present, both the galvanic cell method and the polarographic electrode method are widely used in environmental monitoring, wastewater treatment, aquaculture, and industrial production.

The electrode of the dissolved oxygen measurement sensor consists of a gold or platinum cathode, a silver counter electrode (silver) with current, and a silver reference electrode without current. The reference electrode is mainly responsible for calibrating the cathode potential of the sensor. The electrode of the sensor is placed in an electrolyte solution such as KCl and KOH, and the water to be measured is separated from the electrode by a diaphragm wrapped around the sensor. Doing so avoids the leakage of the electrolyte and prevents the electrolyte in the electrode from being contaminated by the substance in the water body and protects the sensor. In practice, a polarizing voltage is applied between the counter electrode and the cathode. The dissolved oxygen in the water to be measured will be transmitted through the diaphragm, so that the oxygen molecules react with the electrode cathode and are reduced to hydroxide ions: $O_2+2H_2O + 4e- \rightarrow 4OH^-$. The silver chloride in the dielectric reacts with the counter electrode as well: $4Ag^++4Cl^- \rightarrow 4AgCl + 4e^-$. During the reduction of oxygen molecules, the cathode will release four electrons, which flow to the generator to form a current. The magnitude of the current is positively related to the content of oxygen molecules in the water. The electrical signal is transmitted to the transmitter, and the dissolved oxygen content of the water can be determined using the relationship between the oxygen content and the oxygen

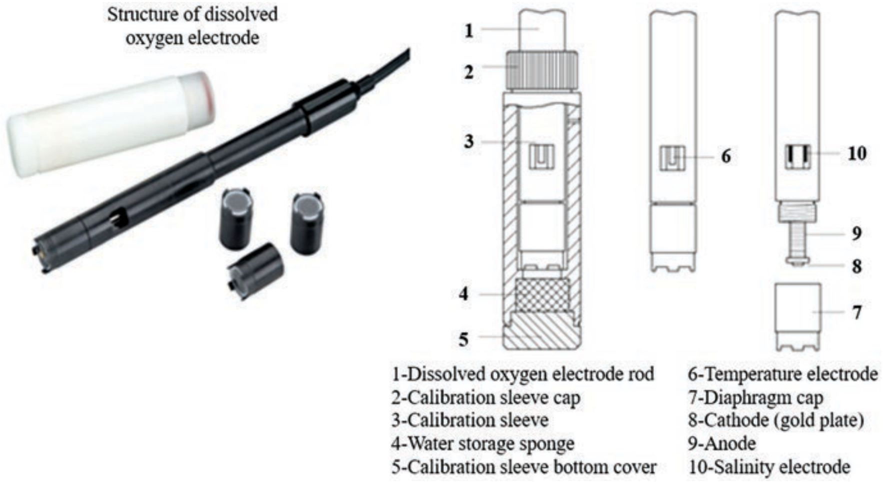

Fig. 7.10 Electrode structure diagram

partial pressure stored in the chip and then displayed in digital form. The structure of the dissolved oxygen electrode is shown in Fig. 7.10.

7.3.3.4 pH (Potential of Hydrogen) Sensor

The Role of pH in Aquaculture

As the most basic property of water, pH is a major indicator of water quality that affects the degree of dissociation of weak acids and bases in water; reduces the toxicity of chlorides, ammonia, hydrogen sulfide, and so on; and influences water quality changes, growth and decline of biological reproduction, corrosiveness, and water treatment effects. The pH value of aquaculture water is one of the major factors affecting the feeding and growth of farmed fish, which is why it is important to determine the pH of water. The suitable environment for fish to grow is slightly alkaline water with a pH of 7.0–8.5, and when pH exceeds 9.0 or falls below 6.0, the growth and reproduction of farmed animals will be threatened.

Changes in water pH have varying degrees of impact on the growth stages of fish. A decrease in pH will lead to increases in H_2S content and the H^+ ion concentration in fish blood. The functions of hemoglobin and various enzymes in fish are destroyed, leading to acidosis and physiological hypoxia reaction, which then makes fish float to the surface of water due to hypoxia. An increase in pH will increase the toxicity of ammonia nitrogen, damage the gills and other tissues of fish, affect their breathing status, and may even cause death from suffocation. The pH value of aquaculture water also impacts the dissolved oxygen and decomposition of humus in the water. As a key criterion used to measure the suitability of the water quality for fish farming, pH value determines the chemical status of the water quality and the biological reproduction in water and directly affects the growth and reproduction of farmed animals.

The growth and reproduction of microorganisms in water bodies are also affected by changes in pH. In water with a lower pH value, phosphate is affected and dissolved, microbial activity is inhibited, and the metabolism of organisms in the entire water body is decelerated. If the water body exceeds the alkaline threshold, the activity of microorganisms and their degradation of organic matter will be affected, thereby decelerating the cyclic absorption and utilization of substances in the water body. To ensure high-speed and stable production, the pH value ought to be maintained within a safe range.

pH Detection Method

Test strip method, acid-base titration method, and potentiometry are several commonly used pH measurement methods.

There are two types of test papers: litmus paper and pH paper. Using pH paper to measure the pH value is the easiest method at present. The measuring principle of this method is to allow the test paper to react with acid and alkaline solutions of different pH values. When different colors appear, one ought to compare it with a standard color chart to determine the pH value of the solution. This method obtains the pH value of the water body by comparing the color of the test paper. Due to the subjective differences in color recognition, high error rate, and poor measurement accuracy, this method cannot meet the high precision requirements of pH measurement in industry and medicine. The method can only be adopted for experiments and simple measurement of pH solution. The litmus paper allows for qualitative test of the acidity and alkalinity of aquaculture waters, yet it cannot be used to measure the pH value of the water body. The titration method determines the end point of the titration based on the measured potential change. In the process of measuring the pH value of the solution by titration, a galvanic reaction will occur between the indicator electrode and the reference electrode. When an acidic or alkaline reagent is dropped into the solution to be tested, it will be stirred by the magnetic stirrer, and the concentrations of H+ and OH- ions will change accordingly. By the same token, the potential difference between the electrodes also varies. When the titration test solution reaches a certain value, the potential difference between the electrodes changes abruptly, so that the end point of the titration can be determined. Moreover, the pH value of the test solution at this time can be deduced according to the pH value of the titration reagent and its volume. In terms of accuracy, the acid-base titration method outperforms the test paper method, but it also involves complicated operation steps as well as time-consuming calculation processes, which is why it is not suitable for on-spot and real-time measurement.

Based on the theoretical basis of electrochemistry, the ion-selective electrode measurement method adopts a biochemical film that is sensitive to a specific ion to form a corresponding electric potential after reacting with the ion. Additionally, a corresponding functional relationship exists between the potential and the ion concentration. Via analysis and calculation, the concentration of this kind of ion can be determined. It is noteworthy that the ion-selective electrode is only sensitive to a certain kind of ion. This method features high measurement accuracy and sound stability. The measurement range falls within 0.00~14.00 pH, and it also enables online measurement. Due to the above factors, this method is now used extensively. Potentiometric methods have gradually matured, and ion-selective electrodes have also become commercially available. Ion-selective electrodes are a type of electrochemical sensor that uses membrane potential to determine the activity or concentration of ions in a solution according to the Nernst equation.

In order to achieve online detection of pH in aquaculture on an ongoing basis, potentiometric method is adopted. The primary component of the ion-selective electrode is a glass bubble. At the lower part of the glass bubble, a special glass film can be found. The sensitive film is Na2O ($x = 22\%$) and CaO ($x = 6\%$) sintered, the glass bubble is filled with an internal reference solution (a certain pH solution), and an internal reference electrode (silver-silver chloride electrode) is inserted into the solution. When the sensor is placed in the farming water, the glass film ion exchange occurs between cultured water bodies to form a membrane potential, and a potential difference associated with the pH value is generated on the inner and outer layers of the glass membrane.

7.3.3.5 Water Salinity Sensors

Water salinity refers to, in addition to the content of sodium chloride, magnesium chloride, magnesium sulfate, magnesium carbonate, and other salts containing various elements such as potassium, iodine, sodium, and bromine.

Although water contains numerous types of minerals, most of them have low solubility. Salinity in water refers to the content of eight major ions, calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), potassium (K^{+}), bicarbonate (HCO_3^{-}), carbonate (CO_3^{2-}), sulfuric acid roots (SO_4^{2-}), and hydrochloride (Cl^{-}), which account for more than 99% of the salinity in water. Water hardness is mainly determined by calcium and magnesium. When the calcium strength approximately equals the total alkalinity, the water has better buffering power, stronger anti-stress ability, and more stable water quality.

Aquatic organisms can adapt to the salinity of the water to a certain extent, and the osmotic pressure in the organism is closely related to the salt content in the water. Fish and shrimp can only survive in water with appropriate salinity. The range of salinity that fish and shrimp can adapt to at different growth stages differs and usually increases with age. These creatures adjust the osmotic pressure in their body to adapt to salinity change. When the ion concentrations of body fluids and external fluids are different, the acid-base balance in the body may be disrupted due to changes caused by dehydration or filling and changes in the concentration and ratio of various ions. Although fish and shrimp can adapt to different salinity water by adjusting the osmotic pressure, a certain limit exists. When the salinity is too high or too low, i.e., beyond the ability of the fish and shrimp to adjust the osmotic pressure, these creatures will “thirst to death” or “swell to death.” Salinity mainly affects the growth and development of farmed animals, chloride cells in the gills, electrolytes in plasma, and mitochondria of succinate dehydrogenase. In the early stage, relying on chemical analysis to determine the salinity of a solution by measuring the weight of dissolved salts in a certain solution has proved to be inaccurate, and the entire measurement process is time-consuming.

In recent years, the density and conductivity measurement methods, the measurement methods adopted by the Vernier salinity sensor, have become the primary methods used for salinity measurement. In the water to be measured, the current flows with the movement of the ions, and the Vernier salinity sensor measures the electric power between two electrodes when they are inserted into the solution. Therefore, as the ion concentration in the water increases, the conductivity value will also increase. It can be seen that the measured data signal of the salinity sensor is actually the conductance, which is the inverse of the resistance. In the International System of Units, the unit of conductance is siemens, and the conductivity of water is usually measured in microsiemens or μS units.

The salinity sensor uses alternating current between the electrodes, which prevents the ions in the solution from completely migrating to the two electrodes. As shown in Fig. 7.11, in each cycle of alternating current, the polarity of the electrode is reversed, and so is the direction of ion flow. This design prevents phenomena including electrolysis and polarization that reduce the accuracy of the sensor from occurring at the poles. Therefore, the salinity sensor not only brings zero destruction to the water sample but also significantly reduces the formation of electrode redox products.

7.3.3.6 Ammonia Nitrogen Content Sensors

Ammonia nitrogen, an indicator of water quality that calls for special attention in modern aquaculture, mainly comes from three sources, that is, the excrement of aquatic animals, the applied fertilizer, and the feed decomposed by microbial

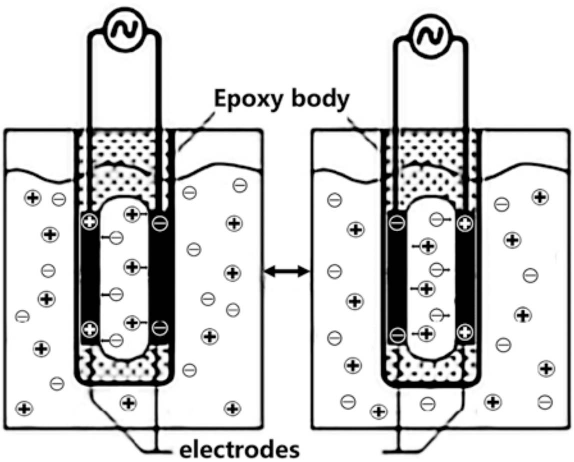

Fig. 7.11 Ion flow direction of salinity sensor

bacteria, feces, and carcasses of animals and plants. In order to prevent ammonia poisoning, fish excretes ammonia nitrogen into the water through the gills and urine, and crustaceans excrete through the gills and antennae glands. Aquatic animal feces and carcasses of animals and plants contain a large amount of protein, which is decomposed by microbial bacteria in water to form amino acid and then further decomposed into ammonia nitrogen.

The harm of ammonia nitrogen to aquatic animals can be either acute or chronic. The hazards of chronic ammonia nitrogen poisoning include reduced food intake, slowed growth, molting failure, tissue damage, and reduced oxygen transport between tissues. Fishes, shrimps, and crabs need to exchange ion with water. Ammonia nitrogen can increase the permeability of gill filaments, damage the ion-exchange function of gills, keep aquatic organisms in a state of stress over the long term, and increase the susceptibility to animal diseases. The most common consequence is prawn black gill disease, which reduces growth rate and eventually leads to death. Acute ammonia nitrogen poisoning is manifested as initial excitement, loss of balance, convulsions, and even death.

When shrimps are small, ammonia nitrogen poisoning is difficult to diagnose; thus it is necessary to promptly measure the ammonia nitrogen content in the water.

The major harms of ammonia nitrogen on aquatic organisms are caused by free ammonia, which is tens of times more toxic than ammonium salts. Free ammonia increases with increasing alkalinity. Ammonia nitrogen toxicity is closely related to the pH and temperature of the water. In general, the higher the pH and water temperature, the stronger the toxicity, and the harm to fish is similar to nitrite.

As the "number one stealth killer" of aquatic organisms, ammonia nitrogen mainly exists in two forms: non-ionic ammonia (NH_3-N) and ionic ammonia (NH_4^+). There is a certain balance between the two forms in water: $NH_4^+OH^- \leftrightarrow NH_3 \cdot H_2O \leftrightarrow NH_3 + H_2O$. The relative concentrations of NH_3-N and NH_4^+ are closely related to pH and water temperature. When the pH and water temperature are appropriate, the two can coexist with a certain ratio. NH_4^+ has certain toxicity to *Nitrosomonas* and *Nitrobacter*, which can inhibit the progress of nitrification, thereby increasing the concentration of NH_3-N in the aquaculture water and indirectly increasing the toxicity of ammonia nitrogen to fish. NH_4^+ can also coerce the normal life of fishes, thus inhibiting their growth.

The main source of ammonia nitrogen's influence on aquaculture is the toxicity of non-ionic ammonia (NH_3-N), which can affect the growth, reproduction, metabolic activity, and osmotic pressure balance of farmed fish and shrimp and cause damage to the water environment. The content of non-ionic ammonia nitrogen is closely related to pH value, water temperature, and salinity. It is stipulated in China's *Fishery Water Quality Standard* that the content of non-ionic ammonia nitrogen should not exceed 0.02 mg/L; however this requirement is often difficult to be achieved in actual practice. Long-term exposure to water environment containing NH_3-N reduces the activity of antioxidant enzymes and the content of antioxidants in fish. NH_3-N, while destroying the antioxidant system of fish, reduces its immunity and makes fish more susceptible to parasitic and bacterial diseases. Furthermore, NH_3-N is also neurotoxic; it enters the blood and is converted into ionic ammonia, which can activate the NMDA glutamate receptor by replacing K+, leading to excessive loss of Ca^{2+} and eventually causing death of nerve cells.

It can be seen that the high ammonia nitrogen concentration in the aquaculture water endangers the normal growth of fish. With the development of large-scale aquaculture, the problem of ammonia nitrogen pollution in water has become increasingly serious. Due to continuous development of the scale of intensive aquaculture, the diversity of aquatic organisms in cultured water gradually decreased, and at the same time, the energy flow in waters slowed down, resulting in the inability to promptly decompose protein materials in excess bait, fish manure, and various biological carrions. When the production rate of ammonia nitrogen in water outstrips its consumption rate, the content of ammonia nitrogen in water gradually increases as time passes by. When it exceeds a threshold value, it will cause toxic effects on fish. Therefore, as a major indicator of environmental pollution in aquaculture environment, ammonia nitrogen needs to be detected in time, so that it can be properly controlled (Wang et al. 2018b).

At present, the commonly used methods for ammonia nitrogen detection include ammonia gas-sensing electrode, distillation-titration automatic monitoring, automatic spectrophotometry, and ion chromatography methods. In light of these methods, the common instruments on the market are photometry, distillation titration, and electrode methods, all of which have both advantages and disadvantages. In terms of natrium reagent colorimetry, the operation is relatively simple, and the reaction is sensitive with the measurement range of 0.025 ~ 2 mg/L^{-1}; however it is easily affected by sulfide, calcium, magnesium, iron, and other metal ions in water and turbidity of water. Moreover, this method requires complicated pretreatment, and the reagent used in the detection process is relatively toxic. Careful treatment of waste liquid after testing is required, resulting in increased workload. Additionally, the optical stability of the method is also poor in detection. In relation to distillation-titration method, the method yields sound measurement results on water samples with high ammonia nitrogen concentration, but when amines (volatile) are present in the water, the measurement results are higher than the actual ammonia nitrogen content. Apart from such a deviation, this method is also time-consuming and labor-intensive. The electrode method features a wide measurement range of 0.03 ~ 1400 mg/L^{-1}, and no pretreatment is required. Plus, the measurement results are not affected by sulfide and turbidity. It can be concluded that this method features convenient and fast operation, low costs, and high accuracy. As eco-awareness of technologies continues to improve, the real-time detection of ammonia nitrogen content in aquaculture water by electrode method would become the dominant detection method.

With the advent of advanced sensing technology, the combination of ammonia nitrogen detection principle and sensor technology gradually moved the detection of ammonia nitrogen content in water toward the direction of intelligent development. The ammonia nitrogen sensor adopts ion-selective electrode technology to measure ammonium ions in sewage water samples. Ion-selective electrodes are equipped with a special membrane, on which only certain types of ions can be adsorbed. A potential is formed on the membrane surface due to the adsorption of ions during the detection. A reference electrode needs to be added to the sensor to measure the adsorption potential difference. During the measurement, deviations occur due to the influence of temperature and potassium ions, and errors are corrected by the internal sensor chip. The reference electrode relies on differential pH technology, which will not affect the detection and will not be affected by the water to be measured, making it stable and drift-free.

7.3.3.7 Nitrite Sensors

Nitrite is an important physical and chemical index that affects the quality of water in aquaculture. The increase in nitrite content indicates that the amount of dissolved oxygen in the aquaculture water is insufficient and the water is seriously polluted. Apart from this, it also indicates a precursor to fish infection. The *Fishery Water Quality Standard* stipulates that the content of nitrite in aquaculture water should be controlled below 0.20 mg/L^{-1}.

The sources of nitrite include exogenous and endogenous components. The former includes water ingress during farming, whereas the latter represents residual bait and daily excreta that enter the water and are decomposed by various microorganisms. As a carcinogen that leads to cancerous cells and tissues, excessive content of nitrite in aquaculture water will also cause poisoning. Nitrite can convert hemoglobin in the red blood cells of fish into methemoglobin, making blood cells unable to combine with oxygen and depriving it of its ability to transport oxygen. Although the oxygen concentration in the water is high enough, methemoglobin cannot fully carry oxygen, which paralyzes the oxygen transport function of each tissue and causes nerve paralysis and even death due to suffocation.

Chronic Poisoning: When the nitrite concentration remains below the lethal concentration but exceeds the tolerance level, it will cause disorder of physiological function, affect growth, or cause other diseases. While the symptoms of chronic poisoning are not obvious and are difficult to observe with the naked eye, it nonetheless seriously affects the normal life of fish. Severe levels of chronic poisoning lead to reduced food intake, decreased motility, lean fish body, and matt surface, symptoms that can be noticed via careful observation. Once the water quality is improved, these symptoms will gradually disappear. On the contrary, if the water quality is not adjusted in time, it will threaten survival rate, especially when severe weather or disease invades, causing great losses.

Acute Poisoning: Visual inspection, similar to the symptoms of floating due to hypoxia, is often accompanied with a series symptom of hypoxia. However, even if the oxygen is increased, the symptoms do not disappear. By the next day, the condition will become more severe, and it cannot be relieved for another several days. Moreover, a large number of deaths may occur as a consequence. The mortality rate can reach over 90%, and the loss can be grave. Fish that died from nitrite poisoning exhibit no apparent posthumous symptoms, and similar to hypoxic death, most of them sink to the bottom of the pond. Relevant anatomy reveals that the gills have become black and swollen, the liver and pancreas are blurred, and the intestines have become congested.

Lower concentrations of nitrite in water can also be poisonous to aquatic animals. When the nitrite nitrogen concentration reaches 0.1 mg/L, the number of red blood cells and hemoglobin of fish and shrimp will gradually decrease, and the oxygen-carrying capacity of blood will gradually be deprived, resulting in chronic poisoning of fish and shrimp. At this time, the feeding rate decreases, and the gill tissue becomes diseased, causing difficulty in breathing and restlessness. When the nitrite concentration reaches 0.5 mg/L, some metabolic functions of fish and shrimp become abnormal, and their physical strength declines. At this point, these creatures are highly susceptible to disease. This stage is followed by large-scale outbreaks of disease, leading to eventual deaths. China's standards for freshwater aquaculture water stipulate that the nitrite nitrogen in aquaculture water should be controlled below 0.2 mg/L^{-1}, and the nitrite nitrogen in crab and shrimp nursery water should be controlled below 0.1 mg/L^{-1}.

In addition, if fish and shrimp live in water with high nitrite concentration for a long time, their physical strength will decline, their feed intake will decrease, their collective immunity will deteriorate, and they will be more susceptible to virus infection and outbreaks.

Via practice, it is evident that symptoms of nitrite poisoning indicate that the high concentration of nitrite in the aquaculture water has been maintained for a long time. In this case, high-efficiency first aid measures must be taken to avoid mass deaths of fish and shrimp and prevent greater economic losses.

Nitrite detectors, mostly used in laboratories, have the ability to accurately detect the nitrite content in aquaculture water. It is widely adopted in environmental protection, food safety monitoring systems, health and epidemic prevention, business administration, noodle product production bases, grain depots, product quality supervision and inspection, shopping malls, and other departments. Due to the time-consuming and complicated process, the nitrite detector failed to enable real-time detection of nitrite content in aquaculture water, which is why a nitrite sensor with real-time online detection capability is used instead.

The working electrode (gold electrode) of the nitrite sensor is in contact with the aquaculture water. The reference electrode (silver-silver chloride electrode) is enclosed in the electrolyte cavity, which exchanges the charge with the external solution by the ion membrane. The NO_2^-in the solution directly oxidizes on the surface of the working electrode to form a current, and the content of NO_2^- in the solution is proportional to the magnitude of the formed current.

7.3.3.8 Residual Chlorine Sensors

Residual chlorine usually refers to the sum of free residual chlorine and compound residual chlorine. Free residual chlorine is unstable and decays quickly, while compound residual chlorine is stable and decays slowly. When the sample water is treated with hypochlorite, residual chlorine still exists, and its decomposition requires a certain time. China has strict standards for residual chlorine in water – the Ministry of Health stipulated in GB 5749-85 *Sanitary Standards for Drinking Water* that the contact time of disinfectant in water is limited to 30 minutes, and its content must not be less than 0.3 mg/L^{-1}. In addition to the above requirements, the residue chlorine in the peripheral water of the outer pipe network should be higher than 0.05 mg/L^{-1}.

When the residual chlorine content is too high, a variety of by-products, such as trihalomethane and other carcinogenic and teratogenic products, will be produced during disinfection, which will easily cause second pollution of water quality and hemolytic anemia. Excessive residual chlorine levels in aquaculture can be lethal to the farming animals. Therefore, effective control and detection of residual chlorine content are essential in water processing.

The mechanism of toxic effects of residual chlorine on shellfish is mainly caused by damage to the gill epithelial cells and the respiratory membrane, leading to hypoxia and suffocation in the body and direct participation in the oxidation of shellfish enzyme systems. Residual chlorine can reduce sublethal parameters such as feed filtration rate, frequency of foot movement, frequency of shell opening and closing, oxygen consumption, foot silk secretion, and fecal volume, thereby depriving shellfish of their ability to adhere. Damage caused by residual chlorine to fish is mainly damage to gills, which hinders the exchange of gills with dissolved oxygen in water. Residual chlorine causes pathological changes in fish gill tissue, such as tissue proliferation, detachment of epithelial tissue, accumulation of a large amount of mucus in the gills, and aneurysms, which affects and hinders the exchange of dissolved oxygen in gills and water. Residual chlorine may also infiltrate into the blood through the gill tissue and then oxidize the reducing hemoglobin that can carry oxygen in the blood to methemoglobin that cannot carry oxygen. It may also inhibit the activity of methemoglobin-reducing enzymes, resulting in a decrease in the blood's ability to carry oxygen.

As science and technology advance, the measurement method of residual chlorine has developed at a high speed. The initial method was chemical determination, which was then replaced by the spectrophotometry according to the current global standard. Ion chromatography measurement was born later on, and the most commonly used method on the market, electrochemical measurement, was also created. Residual chlorine is very unstable in water – when water contains reducing inorganic or organic substances, it is easy to decompose to reduce the content. However, sound results can be acquired using the online real-time monitoring method.

The online residual chlorine analyzer mainly focuses on the sensor principle. The measurement principle is that the electrolyte and the osmosis membrane separate the electrolytic cell from the water sample, and ClO^- can pass through the osmosis membrane, thereby forming a specific potential difference between the two electrodes. The residual chlorine concentration in aquaculture water can be calculated from the current intensity formed by the potential difference.

On the cathode: $ClO^-+2H^++2e^-\rightarrow Cl^-+H_2O$
On the anode: $Cl^-+Ag^+ \rightarrow AgCl+e$

7.3.4 Applications

In recent years, the Digital Agriculture and Rural Informatization Research Center of Zhejiang University has promoted a large number of water quality monitoring equipment in aquaculture information monitoring and automatic environmental regulation. The promotion is mainly implemented in aquaculture technology demonstration households' ponds. This technology adopts advanced sensing technology, wireless sensor networks, and expert diagnostic systems for the collection of aquaculture environmental information, transmission and release of data, and early warning and diagnosis of diseases. In addition, it makes full use of the microcomputer control principle to incorporate aquaculture into the scientific management system and monitors and adjusts the water quality parameters (dissolved oxygen, ammonia nitrogen, nitrite, residual chlorine, water temperature, etc.) of the aquaculture base in real time. At the same time, the collected data is transmitted to the central control room. Through the comparative analysis of the data, early warning and comprehensive control of various diseases are made possible, so that the quality of aquaculture water is always in the best state for fish and shrimp growth. Therefore, this system achieves the goals of intensive production, high efficiency, increased yield, energy efficiency, reduced labor intensity, and reduced pollution to the environment.

P. vannamei are highly sensitive to changes in water. Automatic oxygenation control and online water quality regulation are the critical means to improve the survival rate of *P. vannamei*. The water quality of ponds varies depending on time. During the night, ponds tend to lack oxygen, which is difficult to regulate. However, demonstration households who installed this system can be informed of the water quality of pond and can optimize the water quality in time. Farmers can tap into mobile phones, PDA, computers, and other terminals to keep themselves updated in terms of water quality and obtain abnormal alarm and early warning. Furthermore, they can also depend on the results of water quality monitoring to adjust the control equipment in real time, so as to bring about science-guided aquaculture and management and to achieve the ultimate goals of energy conservation, environmental protection, and increased yield and income (Ma et al. 2007) (Fig. 7.12).

7.4 Summary

From detailed technical analysis presented in this chapter, it can be inferred that safe and efficient livestock and aquaculture farming is dependent upon the support of information sensing. By adopting information sensing technology in livestock and aquaculture farming, farmers can determine, scientifically and accurately, the parameters of the farming environment and the vital signs of aquaculture products. Such information facilitates science-based farming, safe farming, and efficient farming on a technical level. Farmers can also combine information sensing

Fig. 7.12 Intelligent monitoring system for Xinghe crab farming environment

technology with automatic control system to achieve welfare farming, providing the best growing environment for farming products and ensuring their income and the quality and safety of agricultural products.

By adopting products based on livestock- and aquaculture-related technology of Zhejiang University, artificial consumption and the risk farmers expose themselves to have been significantly reduced. The related products and technologies of Zhejiang University contributed to making more complete advanced technologies in the modern-intensive aquaculture production process. At the same time, the generation of pollution in aquaculture is reduced, and the demands on standardized aquaculture are met, thereby ensuring the sustainable development of the aquaculture ecosystem, improving the quality of the ecological environment, and increasing the economic benefits of aquaculture.

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Chapter 8
Agricultural Information Processing Technology

Hui Fang, Bingquan Chu, Yong He, and Xiya Zhang

Abstract Agriculture, as it grows increasingly information-based, will enter the development stage of smart agriculture. At the same time, research on agriculture-related information also demonstrates that it is the future trend for agriculture to become intelligent, precise, standardized, and digitized. This chapter offers a detailed elucidation on the concept of agricultural information technology, key technologies in agricultural information processing technology, and multi-source agricultural information fusion processing technology.

Keywords Agricultural Information · Information processing technologies · Multi-source · Information fusion technologies

8.1 Introduction

Agricultural information processing technology, used to obtain information that relate to agricultural activities through various channels, relies on information processing technology to sort, analyze, process, and mine information, thus facilitating decision-making and providing the theoretical basis for intelligent agricultural control. Agricultural information processing technology is the intersection of multiple disciplines. It shares the complexity of agricultural production and relies on the basic theories and technologies of information processing.

According to the level of intelligence, agricultural information processing is divided into two categories: basic agricultural information processing technology and intelligent agricultural information processing technology. This section, focused on these two categories, illustrates the basic concepts, key technologies, and development trend of agricultural information processing.

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8.2 Basic Concepts of Agricultural Information Processing Technology

8.2.1 Characteristics and Types of Agricultural Information

Agricultural information features both generality and particularity:

- Region-specific. Agricultural operations, susceptible to the external environment, are region-specific. On the one hand, the differences in terms of regional and natural conditions determine the scope and extent of agriculture; and on the other hand, the differences in socioeconomic conditions determine the distribution, structure, management style, and production level of agricultural resources. Therefore, agricultural information is subject to a large number of regional constraints.
- Timeliness. In the process of production, the timeliness of information is critical. For example, with relation to the prevention and control of diseases and pests, though prevention and control measures that are adopted too early may be effective, those that are adopted too late means unnecessary prevention and control which often causes crop losses. Therefore, the timeliness of agricultural information is particularly important.
- Periodic. Most agricultural information regarding the life process of crops are presented in the form of different growth periods, and the requirements for the same element in different growth periods differ significantly. For instance, the general absorption patterns of nitrogen, phosphorus, potassium, and other elements in different growth stages of corn can be summed up in the following way. At the seedling stage, growth is minimal, and the amount of absorption is also small; with the increase of the growth at the early stage, absorption increases and accelerates, reaching the peak at flowering stage; and at last, the organic nutrients are concentrated and transported to the grains, from the flowering to the filling stage.
- Comprehensiveness. Agricultural activities are complex. An agricultural phenomenon is the synthesis of multiple factors. For example, the growth of crops is a comprehensive reflection of multiple factors, such as soil, fertilizer, moisture, and temperature, and the estimated price trend of agricultural products is the result obtained via comprehensive analysis of massive data in multiple markets in a certain period.
- Hysteresis. As organic and living bodies, crops are resistant to environmental changes, manifested as lags of information. For example, it takes a period of time for fertilizers to be effective, and it also takes time for deficiencies of a given nutrient to manifest itself. Hence, the processing of related information must take timeliness into consideration.

8.2.2 Agricultural Information in IoT

8.2.2.1 Composition of Agricultural Information

Agricultural IoT mainly includes three levels: the perception layer, the transmission layer, and the system application layer. The first layer is the perception layer. Sensor nodes including RFID barcodes, sensors, and other devices are used to achieve real-time and dynamic sensing, rapid identification, and information collection. More specifically, the primary information collected by the perception layer include information that relate to farmland environment, soil, and nutrients and physiology of crops. The second layer is the transmission layer, which realizes long-distance wireless transmission of information collected. In agricultural IoT, this layer is mainly reflected as the collection and transmission of large-scale farmland information. The third layer is an application system that provides intelligent management through data processing. When it is adopted in combination with agricultural automation equipment, the system will be able to save resources, protect the environment, and improve product quality and yield. The three levels of agricultural IoT allow it to fully sense information, reliably transmit data, effectively optimize systems, and intelligently process information (Nie 2012).

Based on the analysis of the major areas for the application of agricultural information technology and the main sources that generate big data, it can be concluded that agricultural IoT information mainly involves data in the following areas:

Big data on production process management, including facility planting, facility breeding (livestock and aquaculture, etc.), precision agriculture, etc. It is an urgent task for information-based agriculture to improve precise monitoring, intelligent decision-making, science-based management, and regulation of the entire production process.

Big data on agricultural resource management, covering land, water, biological resources, production materials, etc. Agricultural resources in China are scarce, and the environment and biodiversity are degraded; hence, we must further optimize the allocation and use of resources to achieve sustainable agricultural development with high yield, high quality, and energy efficiency.

Big data on agricultural environment management, covering soil, atmosphere, water quality, meteorology, pollution, disasters, etc. Comprehensive monitoring and precise management are needed in this regard.

Big data on agricultural and food safety management, including production environment, industrial chain management, pre-production, post-production, storage and processing, market circulation, logistics, supply chain, and traceability systems.

Big data on agricultural equipment and facility monitoring, covering the monitoring of equipment, remote diagnosis, service scheduling, etc. In the above applications, the environment and resources, production process, product safety, market conditions, and monitoring and prediction of consumption are the key.

Big data generated by research activities, including remote sensing data on space and ground, and data generated by biological experiments, such as gene maps, large-scale sequencing and genomes, macromolecules, drug design, etc.

8.2.2.2 Basic Processing Methods of Agricultural Information

The basic processing method of agricultural IoT information is the concrete embodiment of agricultural information technology in agricultural applications. In view of the characteristics of the agricultural information, the basic methods of agricultural IoT information processing include data storage, format conversion, data query, retrieval, deeper data analysis, and mining. According to the degree of intelligence of agricultural information processing technology, it can be divided into basic agricultural information technology and intelligent agricultural information technology.

Basic agricultural information technology refers to the establishment of various types of agricultural databases and the combination with computer networks, mobile Internet, "3S" technology, and other technologies. Its main function is to provide dynamic information. Intelligent agricultural information technology is an important means of combining modern information technology and agricultural science and technology on the basis of basic agricultural information technology to realize the effective transmission, rational analysis, and intelligent application of agricultural information. The specific content includes agricultural expert system and agricultural intelligent decision support system.

This chapter mainly deals with basic agricultural information technologies.

8.3 Key Agricultural Information Processing Technologies

Key technologies mainly involve agricultural data storage technology, data search technology, cloud computing technology, geographic information system, image processing technology, and standardization of agricultural IoT data.

8.3.1 Data Storage Technology

In agriculture-related production and management, a large amount of data will be generated. These data, while guiding current production, come with reference values for production in later stages. The application of IoT has brought agriculture into the era of big data. If information is not properly stored, it will lead to loss of data or ineffectiveness thereof. In data processing, the basic links are the collection, storage, classification, retrieval, and transmission of data, which are also called data management. Data storage technology is a specialized technology for managing complex data that come in lager numbers.

8.3.1.1 Concept of Database

A database is a warehouse that organizes, stores, and manages data according to the data structure. Data in the database is organized, described, and stored according to a certain data model that features less redundancy, higher data independence, and easy scalability, and such data can be shared among users. The following constitutes a brief introduction of five types of databases, namely, document database, time series database, spatial database, relational database, and graphic database.

Document Database

As a type of database system that stores and manages a large number of structured documents, document database not only provides functions for document expression, organization, storage, and access but also offers deep processing functions for documents, such as text mining and automatic abstracts.

The major difference between document database and traditional database systems is that the operations in the traditional database are deterministic data queries, while those in the document database are based on semantically relevant queries in addition to the exact matching of strings. Furthermore, in traditional databases, information is divided into discrete data segments, while in document databases, documents are themselves the basic unit for processing information.

Time Series Database

Time series database is composed of time series, which is an ordered set of sequence values or events that change over time.

Time series database is defined relative to the static database. There are two differences between them. First, the static database includes a series of records, and the order of the records is arbitrary. However, in a time series database, records cannot be arranged arbitrarily, and certain attributes in the records are time-stamped; thus the arrangement is inherently related. Second, in a static database, attributes are independent of each other, while in a time-series database, attributes are a function of time and are related to each other.

Spatial Database

Spatial database is the sum of application-related geospatial data stored on computers via a geographic information system. Spatial database is generally organized in the form of a series of files with a specific structure. Traditional databases are not suitable for the representation and storage of spatial data, and cannot support complex objects (such as graphics and images). Compared with traditional database systems, spatial databases suffer from the disadvantages of massive data sets, high accessibility, and complex spatial data models.

Spatial data are express in two ways: vector and raster. The raster method divides the two-dimensional space of the geospatial entity into regular subspaces. Therefore, raster data at different levels share a common basic element (subspace) division. Its advantages are simple structure and easy operation, and its disadvantages include large data storage, low accuracy, difficulties in establishing the topological relationship between features, and complicated operation of a single target. The vector method describes the spatial elements of geospatial entities with points, lines, and surfaces and establishes clear spatial relationship between geospatial entities. Its advantages are high accuracy, small data storage, easy expression of the topological relationship between entities, and easy manipulation of a single target. The disadvantage is that the data structure is complex, and it is generally time-consuming to perform a large number of calculations during spatial analysis and overlay operations (Liu 2012).

Relational Database

The relational model of relational database is "one-to-one, one-to-many, many-to-many." The model refers to the two-dimensional table model; hence a relational database is a data organization composed of two-dimensional tables and their connections. As they are based on the Structured Query Language (SQL) used, these database systems are widely known as SQL databases. The current mainstream relational databases include Microsoft SQL Server,[1] Microsoft Access, Oracle, My SQL, DB2, etc.

Data in a relational model is usually represented by a database table (schema), and objects of the same type (i.e., the same number of attributes with the same type and format) are combined in a table for data structuring. Relational databases store data in rows, and each row has the same number and type of data columns. In addition, data in a relational database is typically normalized, resulting in the creation of multiple tables. Moreover, querying data distributed across multiple tables requires reading and integrating information from one or more different tables. The process of integrating information is based on the matching values of the primary and foreign keys of multiple tables in a relational database, a process called joining tables.

In addition, a major property of relational databases is the ACID principle, which defines a set of rules to ensure data integrity. ACID is an abbreviation of the four basic elements for the correct execution of database operations, that is, atomicity, consistency, isolation, and durability (Wu 2015).

8.3.1.2 Open-Source Database and Its Agricultural Application

The open-source database features low costs, strong performance, open-source code, easy usage, and multi-platform support. Furthermore, this type of database ensures high reliability, high scalability, and multi-language support; thus it is widely used in small and medium-sized enterprises. The scales of agricultural information are large, and the sources are restricted by regions. Generally speaking, the distribution of agricultural information is relatively scattered, and distributed organization and management have become a critical approach. At present, most agricultural resource management platforms still depend on traditional distributed

[1] *Disclaimer*: Commercial products are referred to solely for the purpose of clarification and should not be construed as being endorsed by the authors or the institution with which the authors are affiliated.

database to manage data. Its efficiency is low, the storage capacity of the system is limited by the capabilities of the database management system it depends on, and the support for the management and release for data resources is weak (Yang et al. 2011). Because of the fact that distributed storage and management of various data on a distributed open-source database are scalable and highly fault-tolerant, this approach has become the trend of agricultural databases in the future.

8.3.1.3 Mainstream Database Products and Their Agricultural Applications

The market currently abounds with database products, and the choice of appropriate databases for IoT products is something that ought to be taken into consideration.

In the twenty-first century, agricultural information technology plays an increasingly important role in agricultural development. The application of agricultural technology, especially IoT technology, will accelerate agricultural development, allowing it to enter the age of information. Information in agriculture are relatively large, wide, and scattered. Modern information technology composed of computer technology and communication and network technology has fundamentally transformed the production, transmission, and acquisition of information, and networks have become the largest distribution center for information. The prerequisite of building an information network is to establish a layer of database management software, located between users and databases, that provides a way for users or applications to access databases for functions that include the establishment, query, and update of data. Databases play an important role in strengthening the foundation of agriculture, and the construction of database is one of the major building blocks for information systems in agriculture. Such databases achieve computer-enabled management of agricultural resources, thereby improving the speed of querying, processing, and sharing of information and providing services for production management, policy formulation, and promotion of related research in agriculture.

8.3.2 Data Search Technology

With the development of Internet technology, agricultural information are becoming ever more abundant in both number and type. For example, agricultural information in China is distributed and stored in the form of databases, research websites, and government web pages. Although great progress has been made with regard to information-based agriculture, there are still many problems, including insufficient utilization of data, data stored in the physical state that lie idle, etc. The rational and effective use of these information resources would provide considerable technical support for agricultural development. Data search technology is a technology that adopts search engines to automatically collect information from the Internet and organize and process the original document for users to query. It is noteworthy that what lie at the core of data search technology are search engines.

8.3.2.1 Search Engine

Search engine refers to a system that collects information from the Internet using specific computer programs in accordance with certain strategies. After organizing and processing the information, search engines provide users with retrieval services and display the retrieved information. Search engine, as a retrieval technology that works on the Internet, aims to improve the speed at which people obtain information and to provide people with a better network environment.

Finding information in such a vast ocean of information on the Internet is like "seeking a needle in a haystack," and search engine is the technology that emerged to solve this problem. Search engines use certain strategies to collect and discover information on the Internet; to understand, extract, organize, and process information; and to provide users with retrieval services for navigation. Search engines work in the following steps.

Collecting Information
The collection of information is basically automatic for search engines, as they use automated search robot programs called spiders to connect to hyperlinks on every web page. The robot program is based on the hyperlinks of web pages that lead to other web pages. These robots start from a few web pages and become connected to all other web pages. Theoretically, a robot can traverse most web pages if there are proper hyperlinks on the web pages.

Organizing Information
The process by which search engines organize information is called "indexing." Search engines save the information they gather and arrange them according to certain rules. By doing so, search engines are able to identify the required information without having to reexamine all the information in a timely fashion.

Receive Inquiry
Users issue a query to the search engine, which then accepts the query and returns information to users. Search engines receive queries from many users at all times, almost simultaneously. They check their index according to the requirements of each user, find the information the user needs within short periods of time, and return it to the user. Currently, the results returned by search engines are mainly in the form of web links. Through these links, users can reach the web page where the information they need is located.

Search engines use certain strategies to collect and discover information on the Internet; to understand, extract, organize, and process information; and to provide users with retrieval services for navigation. Depending on different methods of collecting information and providing services, search engines are divided into directory search engines, robot search engines, and metasearch engines.

Directory search engines collect and classify Internet information according to certain standards, compile them into corresponding directories, and manage directories in a hierarchical and successively itemized manner. Searching information can be entered layer by layer, and the desired information can be identified at last. Yahoo is a typical categorized directory search engine. Such engines are characterized by the addition of artificial intelligence, which leads to higher levels of information accuracy, but the range of such search engines is small and low. Such engines are extremely convenient when retrieving information with obvious professional characteristics. However, the quality of information classification and the user's understanding of information categories will directly affect the query results.

Robot search engines use their internal search robot spider programs to automatically search the content of large and small websites on the Internet. According to the principle of webpage relevance, a corresponding relationship is established between each keyword and all related web pages and is stored in their web servers' database. As long as the user enters a keyword, he can find all indexed web pages that match the characteristics of the keyword, and a brief introduction to the search result is provided in the form of a hyperlink. Users may click on the link to enter the corresponding web resource website and acquire the required information. The search results are usually millions, but the more relevant the information, the higher its position in the search result list. The typical keyword full-text search engine is Google.

Metasearch engine do not have its own index data; instead, it submits user query requests to multiple search engines at the same time; processes the returned results after repeated elimination, reordering, and so on; and returns them to the user as its own results. This type of search engines includes worldwide search, Search, Dogpile, etc. The advantage of metasearch engines is that they can search multiple search engines at the same time, which improves the scope of the query to a certain extent. The disadvantage is that sometimes it is not possible to check all information, and critical information can be omitted.

8.3.2.2 Data Search and Agricultural Application

More than 30,000 agricultural-related websites exist in China, all of which provide rich information on production, markets, regulations, policies, and technologies. The above three types of search engines could provide a handy tool for collecting and using such information, which could bring new vitality to the development of agriculture. Because users of such information are farmers, and considering their educational level and computer operation skills and the complexity of relevant information, the above three agricultural search engines have the following two shortcomings in practical application. First, users are unable to use simple keywords to find the required information. Second, search engines only return thousands of links of web pages, and there is still a long way to go before users can get the information they need. Therefore, specialized and intelligent engines suitable for agricultural information search will be the mainstream of future agricultural information search engines.

8.3.3 Cloud Computing Technology

Cloud computing technology, originated from search engines, is a computing technology developed by Internet companies in the pursuit of low cost and high efficiency. It has now become an important platform for Internet services.

Through cloud computing technology, network providers can form and process tens of millions of data in a matter of seconds, giving rise to network servers with the same powerful functions as supercomputers. On the one hand, cloud computing has changed the traditional resource allocation and distribution pattern and transformed the mode of providing information services on the other. After years of development, cloud computing has gradually substantialized (Zheng 2015).

8.3.3.1 Principles of Cloud Computing

The basic principle of cloud computing is to distribute computing to a large number of distributed computers, rather than local computers or remote servers, and the functioning of corporate data centers is similar to the Internet, allowing companies to allocate resources to corresponding applications and obtain access to computers and storage systems in a demand-specific manner.

Figure 8.1 illustrates a typical cloud computing platform. Users can select service items in the service catalog from the interactive interface services provided by the cloud user terminal, schedule the corresponding resources through the request management system, and distribute requests through configuration tools and configure web applications.

- The service directory is the directory listing that users can access. Users can also modify their own inventory directories.
- The management system and configuration tools are mainly responsible for user login, authentication and authorization, management of available computers and resources, procedures for receiving user requests and forwarding them to the corresponding applications, and dynamic deployment, configuration, and reclaiming of resources.
- The monitoring and statistics module is responsible for monitoring the usage of cloud system resources, so that node synchronization configuration, load balancing configuration, and resource monitoring can be completed in a reasonable and timely manner to ensure the rational allocation of resources.
- The computing/storage resources are virtual or physical servers that are used to respond to user needs.

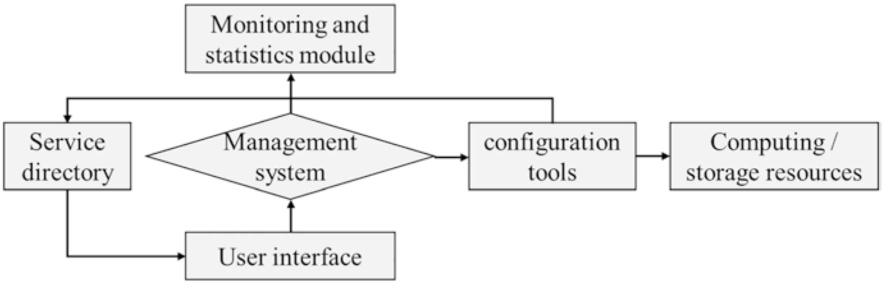

Fig. 8.1 Typical cloud computing platform

8.3.3.2 Type of Cloud Computing

Cloud computing includes two components, namely, cloud platform and cloud service. Cloud platform refers to hardware-based services that provide computing, network, and storage capabilities, whereas cloud services refer to services that are based on abstract infrastructure and can be flexibly extended. It is noteworthy that cloud services are not necessarily based on cloud platforms.

Depending on whether the service is publicly released, cloud computing can be divided into public cloud, hybrid cloud, and private cloud. There is no essential difference between the three in terms of technology, and they only differ in the operation and scope of application. Public cloud refers to companies using cloud platform services operated by other companies or organizations, private cloud refers to companies operating and using cloud platform services, and hybrid cloud shares some of the features of both (Zheng 2012).

Depending on the type of service, cloud computing can be divided into infrastructure as a service (IaaS), platform as a service (PaaS), and software as a service (SaaS). As shown in Fig. 8.2, each layer in the computer network implements a certain function, and there is a certain relationship between layers. The layers in the cloud computing system can be divided, and each layer can complete a user's request independently without the support and services of the other layers.

IaaS

Infrastructure as a service (IaaS) provides virtual hardware resources in the form of services, such as virtual hosting, storage, networking, and database management. Users do not need to purchase servers, network equipment, and storage equipment; instead, their own application systems can be built simply by renting the abovementioned equipment on the Internet. Typical IaaS includes Amazon's elastic cloud (Amazon, EC2) (Zheng 2012). The IaaS layer mainly provides low-cost and high-performance data centers and reliable infrastructure services, including IBM's Wuxi Cloud Computing Center, Century Interconnection's CloudEx cloud host, etc.

PaaS

Platform as a service (PaaS) provides application service engines, including Internet application programming interfaces and operating platforms. Based on application

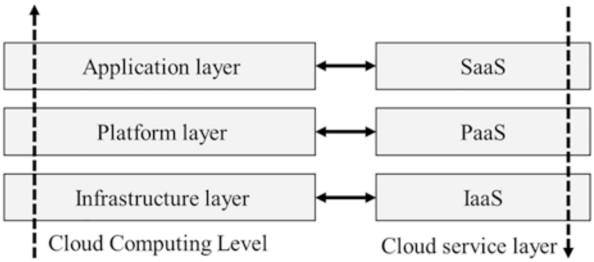

Fig. 8.2 Cloud computing service types

service engines, users can build this type of applications, such as Google App Engine and Microsoft Azure. At the PaaS level, service providers provide encapsulated IT capabilities, such as databases, file systems, and application operating environments, which are usually billed based on user logins.

SaaS
The software as a service (SaaS) layer, focused on the end users of cloud computing, provides Internet-based software application services. SaaS is the most common form of cloud computing at present. In SaaS, service providers are responsible for maintaining and managing software and hardware facilities, and users are able to get access to software through the Internet. Furthermore, users do not have to make any purchase; rather, they only need to rent the software they need. Typical services of this type include Google's online office software and 800 apps (Zheng 2012).

8.3.3.3 Cloud Computing and IoT

A large number of data is produced in agricultural production, covering seed selection, cultivation, harvesting, classification, and processing. However, the cost of implementing complex algorithms on hardware or software is relatively high, and because farmers have lower incomes, they cannot afford the costly modern equipment. The introduction of cloud computing into agriculture, in combination with IoT technology, builds an agricultural data cloud that reduces costs, improves efficiency, customizes as needed, saves resources, and promotes the modernization of agriculture.

Advantages of Reliability
As the amount of data generated in agricultural operations continues to ramp up, the number of servers in IoT has also increased, and as the number of servers continues to increase, the probability of errors in server nodes rises. Via cloud computing, redundant backup technology can be used to repair error server information, which significantly improves the reliability of agricultural operations.

Advantages of Cost
The server's hardware capacity is limited, and it crashes when the trafficking exceeds the limit. Additionally, access to data in IoT is uncertain and dynamic. Because decision-making in production requires comprehensive analysis of data from previous years, as time goes by, the huge amount of information accumulated can be very demanding on server hardware. The use of cloud computing technology can dynamically increase the number of servers in the cloud, which not only reduces production costs but also meets the need of IoT access at any time.

Advantages of Computing Power and Storage Power
Cloud computing uses parallel technology, distributed computing technology, and grid computing technology to integrate multiple computer entities into a powerful computer system through the network. It is capable of providing powerful computing functions just like supercomputers, and cloud storage facilitates the storage of massive agricultural information.

Advantages of Data Mining
The data generated by IoT (including sensor data, RFID data, two-dimensional code, video, pictures, etc.) is fairly complicated. In the process of production, IoT data are real-time and uninterrupted. As time goes by, the amount of data continues to increase, and there might not be any upper limit to it. Cloud computing, the brain of IoT mining, guarantees distributed parallel data mining and efficient real-time mining. As a common mode of data mining, cloud services ensure the efficiency of data mining, realize the sharing of data mining, and lower the technical threshold of data mining. Cloud computing, the core of IoT, achieves the real-time and dynamic monitoring and IoT-enabled management, making intelligent analysis possible.

Integration of Cloud Computing and IoT
IoT is the result of deepening developments of information, and cloud computing is bound to be created as IT continues to mature. Cloud computing provides various services in a virtualized way, and even IoT itself exists in a cloud-based manner. In a way, IoT needs the help of cloud computing to solve certain problems, and IoT itself is a form of cloud computing application. The integration of cloud computing and IoT in the future will certainly provide strong support for the transformation of agricultural production.

8.3.4 Artificial Neural Network Technology

Artificial neural network (ANN) is a complex network with many simple processing units (i.e., neurons) interconnected with learning, memory, and induction functions. It is a mathematical simulation of the nervous system of the human brain that is relied on to achieve learning. Moreover, ANN imitates the way in which signal processing is done in human brains.

Artificial neural network is a highly nonlinear, mega-scale, continuous, and dynamic system. In addition to the common characteristics of nonlinear dynamic systems, other major characteristics of ANN include continuous nonlinear dynamics, holistic concept of networks, large-scale parallel distributed processing, high robustness, and ability of learning and associations.

8.3.4.1 Principle of Neural Network Technology

Artificial neural network (ANN), a mathematical model that simulates biological neural networks for information processing, consists of simple and adaptive information processing units connected through a topological structure in a massively parallel manner. Depending on the differences in network topology, neuron transfer functions, learning algorithms, and system characteristics, ANN models come in many forms. Among them, back propagation (BP) neural network is currently one of the most widely used artificial neural networks. Its structure is divided into input layer, hidden layer, and output layer. The core idea is to adopt error correction learning algorithms (also known as delta learning rules) for the adjustment of network parameters, thus continuously improving the accuracy of the network's response to input patterns.

8.3.4.2 Mathematical Model of Neuron

The structure and model of artificial neurons are shown in Fig. 8.3. Regarding the *i*th neuron in the figure, when the sum of time is not considered, the change of the membrane potential u_i is equal to the linear combination of the input signal I and the weight$W$:

$$u_i = \sum_{k=1}^{n} W_k I_k \tag{8.1}$$

According to the change of membrane potential u_i and the activity x_i at this time, the activity $x_i(t)$ of the *i*th neuron at time t can be determined:

$$Q_i(t) = f_i(x_i) \tag{8.2}$$

$f_i(x_i)$ is an arbitrary function containing the threshold value, also known as the output function, and is determined according to different models. $Q_i(t)$ is the output of the *i*th neuron.

The mathematical theory of neural networks is essentially a nonlinear one, and BP neural network can be regarded as a nonlinear mapping between input and output sets. To realize such a nonlinear mapping relationship, it is not necessary to study the entire internal structure of the system, and one only needs to simulate the internal structure of the system by examining a limited number of samples.

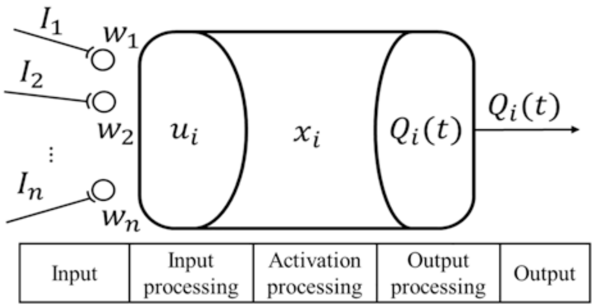

Fig. 8.3 Artificial neuron model

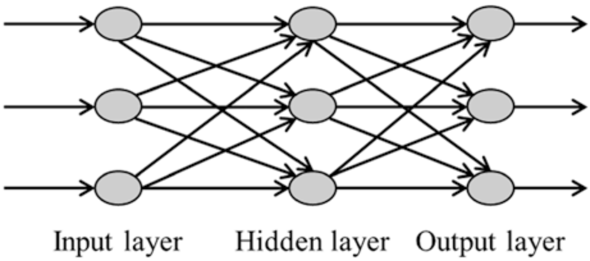

Fig. 8.4 BP network structure diagram

As shown in Fig. 8.4, the standard BP model consists of three neuron layers: the input layer, the hidden layer, and the output layer. BP network, deemed as a nonlinear mapping between input and output sets, uses offline multilevel error correction gradient descent to learn offline. Error back propagation learning only implements gradient descent on the surface of the cost function. Due to the existence of nonlinear hidden units in BP networks, multiple minima exist in the cost function. Therefore, gradient descent cannot guarantee the holistic minimum. It can be proved that in the case where the hidden layer nodes can be freely set as required, a three-layer BP network can be used to approximate any continuous function with arbitrary precision. In addition, there are many classic CNN models, such as LeNet5, AlexNet, VGG, GoogLeNet, and ResNets.

8.3.4.3 Application of Artificial Neural Network in Agriculture

A neural network model is able to learn from past events, and a superior network model is capable of making predictions based on experience. In order to improve the performance of agricultural remote sensing image retrieval, Ye et al. (2019) proposed a remote sensing image retrieval method using convolutional neural network classification capabilities. In Ye's research, the fine-tuned convolutional neural network model is used to extract the retrieval features of the query image and the weight of each category. Then, the category accuracy and the initial ranking results of the retrieved image determined by the CNN model are used to calculate the category precision. The test results demonstrated that the average accuracy of the retrieval method in the PatternNet data set reached 97.56%.

Neural networks can perform classification processing. In agricultural engineering, many classification problems exist, including the hierarchical classification of agricultural products. Given that the classification index involves volume, size, shape, weight, color, biological characteristics, and so on, many products could only be classified and graded manually in the past. The computer vision system is used to input the product appearance information into the computer. Images are preprocessed according to the classification characteristics of the image and are then forwarded to the neural network for learning. The learning internal network system, used for classification, yields satisfactory results.

Neural networks can be applied to process control. Though it is difficult to describe the production process of many processing industries with accurate mathematical models, neural networks can learn from the data accumulated in the production process, allowing neural networks to fully reflect the impact of process control variables on the production process and predict product quality. Therefore, neural networks can be used to control the production process in real time, thus optimizing the production process. Wang (2016) extracted the acoustic signal characteristics related to egg cracks and used artificial neural networks to construct a discriminant model to verify the discriminant effect and designed an FPGA + DSP-based online detection system for egg cracks. The artificial neural network is trained with all 26 features and filtered features, respectively, and the results are compared. The results demonstrate that this method significantly reduces the amount of calculation while ensuring the accuracy of detection, which bears practical significance.

8.3.4.4 Artificial Neural Network Promotes Smart Agriculture

With the development of the mobile Internet, IoT, and cloud computing, we are bound to be surrounded by a vast ocean of data. In addition, the level of intelligence of today's artificial neural network technology is getting closer to human intelligence; as a result, the overall structure of modern societies is becoming more and more "smart." In the future, human beings will have a more comprehensive ability to perceive the world. But because of the huge amount of information that is generated every moment, ordinary people and traditional technologies fail to cope with such data and are increasingly enslaved by it. What this means is that further innovations are required in the way information is communicated between humans and nature. Relying on the new generation of information technology, information can be more "smartly" mined and used to provide more "smart" decision-makings and responses. The emergence of "smart agriculture," achieving efficient, high-quality, energy-efficient, environmentally friendly, and sustainable development in agricultural production, will inevitably become the future trend in agriculture.

“Smart agriculture” is a huge system or a top-level virtual concept. The specific implementation of smart agriculture is composed of subsystems in various fields, covering intelligent facility agriculture, intelligent agricultural conditions, intelligent crop protection, intelligent irrigation, intelligent market management, and other subsystems. As smart agriculture deepens, advanced technologies such as IoT, cloud computing, big data, and semantic networks will be increasingly applied. The key to smart agriculture is to fully integrate knowledge bases and model bases in various fields; to adopt inference, analysis, and other mechanisms to make predictions; and to provide intelligent control and decision-making management. At present, smart agriculture is far from real intelligence, but as the Chinese saying goes, the journey of thousands of miles begins with the first step. For example, in facility agriculture, through the automatic network monitoring system, multiple environmental parameters in the greenhouse are collected in real time, including the temperature and humidity of air, soil temperature and humidity, CO2, light, dew temperature, and other environmental parameters. Furthermore, the specific equipment (such as those used for irrigation, shading, ventilation, heating, and cooling) is automatically turned on or off. Additionally, according to user needs, automatic monitoring for the comprehensive information on facility agriculture is offered, and a scientific basis for automatic control and intelligent management is also provided. By monitoring information on crops and their growth environment, various disaster information, and so on, the appropriate time for irrigation and fertilization can be determined, early warning can be issued, and effective disaster prevention and mitigation measures can be adopted. Although these are only the preliminary applications of smart agriculture, they do contribute to the transformation of production methods.

As a primary industry in China, agriculture is facing severe challenges, such as increasing demand for agricultural products, scarce resources, frequent disasters caused by climate change, fragile ecological security, and continued decline in biodiversity. In light of all this, we should consolidate the information-based agriculture with the agricultural IoT and cloud computing technology as its core, thus improving the services of information-based agriculture supported by big data, making new progresses in smart agriculture, and delivering leap-forward development.

8.3.5 Geographic Information System

8.3.5.1 Overview of GIS

Geographic information system (GIS), a specific spatial information system, is a technical system that collects, stores, manages, calculates, analyzes, displays, and describes relevant geographical distribution data in the space of all or part of the Earth’s surface (including the atmosphere). Supported by computer hardware and software systems, GIS technology is used in multiple industries to establish spatial databases and decision support systems of various scales, providing users with multiple forms of spatial query, spatial analysis, and auxiliary planning, and decision-making functions. Moreover, GIS performs comprehensive processing, integrated management, and dynamic access to spatio-temporal data from multiple sources. It serves as the fundamental platform for newly integrated systems and provides geological knowledge for intelligent data collection. At the same time, the application of geographic information systems has also transformed the way in which geographic information is released and exchanged, providing a new way to understand geographic information. In this manner, new geographic information can be analyzed and generated more effectively, and geographic information systems can evolve into a discipline that specifically deals with spatial data.

8.3.5.2 GIS Classification

Thematic geographic information system is a geographic information system designed for specific services. This type of systems, such as crop yield information system, comes with limited goals and special features.

Regional geographic information system, a geographic information system that is based on geographical areas, conducts comprehensive research and provides integrated information services. Such systems, like the National Information System of Canada, can be divided by administrative area; they can also be divided by natural area, such as the Yellow River Basin Information System.

The system of general software tools is a set of software packages with the basic functions of geographic information system, including graphic image digitization, storage management, query inspection, analysis calculation, and multiple outputs. The system is mainly used as support software for geographic information system to build thematic or regional geographic information systems.

8.3.5.3 GIS Composition

A functioning GIS should support the collection, management, processing, analysis, modeling, and display of spatial data. GIS is mainly composed of five parts: system hardware, system software, spatial data, personnel, and application model.

- System hardware includes computer host, data input device, data storage device, data output device, and data communication transmission device.
- System software refers to various programs necessary for the operation of a geographic information system, usually including computer system software, geographic information system software, and application analysis programs.
- Spatial data is a term that refers to the object and content within the scope of the geographic information system.
- Personnel refers to developers. Skilled operators are able to overcome the deficiencies of GIS software functions, whereas those who are not fail to do the

same. The superiority of software cannot make up for the damages that ignorant GIS operators may bring.

- Application model refers to the expression of the rules summarized on the basis of extensive research on the specific objects and processes in the professional field.

The GIS software system consists of six modules, namely, data input module, graphics and attribute editing module, data storage and management module, data analysis and processing module, data output and presentation module, and user interface module.

- Data input module is used to transfer raw data (data from multiple sources and multiple forms) to the system and convert these data from the external format to an internal format that would be convenient for system processing. It mainly consists of vector tracking digitization by hand tracking digitization, raster scanning digitization by scanning digitization, and keyboard input.
- After data input is completed, the graphics and attribute editing module is used to layer, classify, and encode data. It is also used for edition, transformation of coordinates, trimming, edge joining, attribute input and attribute connection, etc.
- Data storage and management module mainly organizes and manages the location, spatial topological relationship, and attribute data of geographic elements (usually points, lines, and surfaces). The specific functions of the module include seamless layer connection, partitioning, spatial indexing, and data access mechanism.
- Data analysis and processing module mainly performs spatial analysis operations and preprocessing operations on data. Including query and extraction operations, raster overlay analysis and vector overlay analysis, spatial clustering, path analysis, resource allocation address matching, and other basic spatial operation functions.
- Data output and presentation module is primarily responsible for the thematic mapping output of data, statistical report output, visual representation of scheme selection, etc.
- User interface module mainly provides user interface, program interface, data interface, and development environment.

8.3.5.4 GIS Application in Agriculture

Based on the characteristics and powerful functions of geographic entities of information, GIS is extensively adopted in the management of resources and environment, planning and zoning, disaster monitoring, and environmental protection for agriculture.

Management of Agricultural Resources and Environment

Management of agricultural resources and environment brings together all kinds of resources and uses GIS statistics and coverage analysis functions to provide resource statistics and the reproduction of original data under diverse conditions according to boundary and attribute conditions. Such management surveys agricultural resources and environmental data through GIS and adopts GIS statistical analysis function to provide the basis for decision-making in resource and environmental management.

Agricultural Planning and Zoning

To achieve agricultural planning, one needs to deal with many problems of different natures and characteristics and conduct comprehensive analysis of multiple factors. The GIS database merges these data into a unified system for professional application models to achieve multi-factor and multi-objective planning, including the suitability evaluation of different types of land and the optimal allocation of resources.

Monitoring of Agricultural Disasters

Comprehensive evaluation of major meteorological disasters, using remote sensing, GIS, and computer technologies, is able to calculate the approximate disaster area based on GIS spatial information and to estimate the potential economic losses. Via the analysis of historical environmental conditions and disasters, one is able to predict the basic pattern of disaster occurrence, spatio-temporal distribution, probability distribution, and hazard levels. Additionally, comprehensive evaluation simulations are made, and the specifics of disasters are predicted, thus facilitating decision-making for prevention and mitigation.

Agricultural Environmental Protection

GIS is used to analyze and process the information obtained by remote sensing. Relying on GIS, the relevant problems are identified in time, and early warning is given accordingly. Moreover, an environmental spatial database is established. The database is then analyzed, and a thematic map of an indicator is drawn, which can express the changes in the environment. The GIS model is used to establish an environmental model for simulation of the dynamic changes of the agricultural environment. The model also provides services for decision-making and management. Any substance in the material world is firmly branded in time and space, and IoT cannot be separated from GIS's location services. In terms of processing spatial information and attributes of matter, GIS is more advantageous. As a spatial geographic information system, GIS is a computer system that can visually support decision-making. It will become the fundamental support system for building IoT and will play an increasingly important role in information society of the future.

8.3.5.5 Development of GIS in Agriculture

Geographic information system is a technology in research on geography that has rapidly matured since the 1960s. It is a new marginal discipline that integrates computer science, geography, mapping and remote sensing, space science, information science, and management science. Furthermore, GIS is also a spatial information system that collects, stores, manages, analyzes, and describes data related to space and geographic distribution based on a geospatial database with the support of computer hardware and software systems. It provides services for geographic research and decision-making. The objects processed and managed by GIS are data on geospatial entities and their relationships, covering spatial positioning data, graphics, remote sensing images, attributes, etc. Such data are used to analyze and process various phenomena and processes distributed in a certain geographical area and to solve the problems of complex planning, decision-making, and management.

From a technical point of view, GIS is currently in a critical period of development. New concepts and new products of GIS are emerging endlessly, and the trend of componentization and network of GIS are becoming increasingly apparent. Component GIS (abbreviated as ComGIS) is based on a standard component platform. In ComGIS, each component can be freely and flexibly reorganized. Additionally, it also has a visual interface and a convenient standard interface. The component platform mainly includes Microsoft's COM (component object model) and DCOM (distributed component object model) and OMG's common object request broker architecture, and Microsoft's COM/DCOM dominates the market status. Based on COM/DCOM, Microsoft introduced ActiveX technology. ActiveX controls are the most widely used standard components in today's visual programming, and most of the new generation of component GIS are ActiveX controls or their predecessors – OLE controls. It can be concluded that component GIS represents the current trend of GIS development.

As the relevant theory improves, GIS is becoming more integrated and intelligent, making it an important tool for decision support. By combining GIS technology with GPS technology, RS technology, expert systems technology, and Internet technology, the functions of the GIS system can be extended, and various geospatial data, attribute data, images, and files on the web can be browsed and obtained from any node on the Internet across regions. Geospatial analysis is then conducted, so that the design of information systems is transformed from the traditional model of self-sufficient data to an open model of online data resources and that timely and reliable information decision support is made available.

8.3.6 Image Processing Technology

Image processing is a method for removing noise. Moreover, it is also dedicated for enhancing, restoring, segmenting, and extracting features from an image using a computer. The adoption of image processing technology in agriculture is fairly recent. Computer multimedia technology, as it matures in recent years, has been extensively adopted in crop growth monitoring; diagnosis of diseases, pests, and weeds; automatic harvest of crops; seed quality detection; identification of deficiencies in crops; and classification of agricultural products. Common computer image processing methods include image enhancement, morphological processing, and image segmentation. The following constitutes a brief introduction of the related image processing technologies.

8.3.6.1 Image Enhancement

Image Histogram Processing

Histograms are the basis of many spatial domain processing technologies. Histogram operations can be used for effective image enhancement. In addition to providing useful image statistics, the information inherent to histograms is also useful in image compression and segmentation. Additionally, histograms are easily calculated in software and are also suitable for commercial hardware devices.

The detection of white foreign fibers is a difficult problem in cotton online detection. Wang et al. (2012) improved the two-dimensional Otsu algorithm by analyzing the gray histograms of white heterosexual fibers and lint cotton. When calculating the probability sum of the target and the background, the probability sum of the sub-diagonal regions of the two-dimensional gray histogram was considered, which reduced the value range of the two-dimensional Otsu algorithm threshold pair. Experiments demonstrated that compared with the one-dimensional Otsu algorithm and the fast-two-dimensional Otsu algorithm, the accuracy and real-time performance of the improved two-dimensional Otsu algorithm are markedly superior, and the algorithm has been successfully applied to actual production. Combining multiple support vector machine classifiers, Zhang et al. (2016) proposed an intelligent rapeseed deficiency analysis and diagnosis method based on non-uniform histogram of HSV color space. In Zhang's research, first, the active contour model was used to segment the rape leaf region, then the HSV color histogram features of the segmented rape leaf region were extracted, and the method of non-uniform quantization was adopted to characterize the color difference of different deficiency rapeseed leaf images. Finally, one-to-many scheme was used to train multiple support vector machine classifiers that are used for the classification and recognition of different lack of rapeseed leaf images. The results demonstrated that this method can identify the types of deficiency in common rapeseed in a more accurate manner, and the overall recognition rate of the five types of deficiency was 93%.

Image Filtering

Image enhancement methods fall into two broad categories: spatial domain methods and frequency domain methods. The former is based on the direct processing of pixels in an image, whereas the latter is based on the Fourier transform of the modified image. Neighborhood processing is adopted to control the image values of the neighborhood and the corresponding sub-images with the same dimensions. These sub-images can be called filters, masks, kernels, templates, or windows. The mechanism of spatial filtering is to move the mask point by point in the image to be processed. At each point, the filter's response is calculated through a predefined relationship. With regard to linear spatial filtering, the response is determined by the product of the filter coefficient and the corresponding pixel value of the area swept by the filter mask.

The output (response) of the smoothed linear spatial filter is a simple average of the pixels contained in the filter mask. The smoothing filter replaces the value of each pixel of the image with the average gray value of the pixels in the neighborhood determined by the filter mask. This process reduces the “sharp” change in image gray. A common smoothing application is noise reduction; however, because the edge of the image is affected by sharp changes in terms of gray level, there is a negative effect of edge blurring in median filtering process, whose major function is to remove the irrelevant details from the image.

A statistical filter is a nonlinear spatial filter whose response is based on the ordering of pixels in the image area surrounded by the image filter, and the value determined by the statistical ordering results replaces the value of the central pixel. A common median filter is counted on to replace the value of the pixel with the median gray level of the pixel. Such filters feature excellent de-noising ability for certain types of random noise and are very effective for processing impulse noise (pepper salt noise).

In order to reduce the noise of the images about crop diseases and pests, Li et al. (2019) proposed an improved adaptive Gaussian filtering algorithm. This method is used to determine the Gaussian standard deviation by calculating the ratio of the center point neighborhood variance in the pixel matrix area of the image to the two-dimensional Gaussian filter function. Additionally, it is also used to dynamically generate a Gaussian convolution kernel and perform noise reduction and smoothing on the lesion image. The improved filtering algorithm provides an optimized means of pre-processing for the image of leaf diseases and pests, thereby improving the accuracy of diagnosis. Yu et al. (2019) proposed a new filtering method to solve the problem that the measured SAR image is widely submerged by noise and that the edge tends to blur when the traditional filtering method is used. In this new method, on the multi-scale wavelet components of the image, the components after de-noising are obtained by setting different thresholds in different coefficients and different directions based on Bayesian theory and the wavelets corresponding to the image edges and other structures extracted based on multi-scale edge detection. Eventually, these reconstructions are fused to filter noise.

8.3.6.2 Image Morphology Processing

Image morphology processing methods mainly include expansion, erosion, open operation, and closed operation. Dilation or erosion is used to convolve the image with the kernel. Dilation is an operation that seeks a local offset, and corrosion, as opposed to swelling, is an operation that seeks to localize. Open operation is performed to etch and then expand. Generally speaking, open operation will smooth the outline of the object and eliminate small burrs, but the local shape of the object remains unchanged. Reversely, closed operation is to first expand and then erode. Similarly, the closed operation will also smooth the contours and eliminate edge burrs, but in contrast to open operation, it usually eliminates isolated spots and fills in cracks and holes in the contour lines.

In order to solve the problem of inaccurate fruit recognition during the operation of tomato picking robots, Sun et al. (2019) proposed a target extraction algorithm based on a combination of geometric morphology and iterative random circles. This algorithm can effectively segment and identify the fruits that are stuck in the image. The accuracy rate of fruit recognition using this algorithm reached 85.1%. To some extent, this algorithm solves the problem of fruit segmentation when multiple fruits are stuck or blocked in a complex environment. Wang et al. (2019) used the method of morphological erosion to optimize the segmentation results when implementing the segmentation of corn stubble rows and removed false segmentation caused by threshold errors, such as burrs, isolated points, and certain inter-row noise. The average error rate of Wang's experiment relative to the target area was 24.68%, which is far lower than the iterative method (90.67%) and the OTSU method (86.42%).

8.3.6.3 Image Segmentation

RGB Segmentation Model

Due to the inherent characteristics of the human eye, the colors we see are various combinations of the so-called primary colors: red (R), green (G), and blue (B). In the RGB color model, the image represented is composed of three image components, and each component is its primary color image.

In agricultural production, image segmentation technology is used to separate soil and vegetation, so that weeds and crops can be further differentiated. In general, for crops whose main pigment is chlorophyll (such as corn, soybeans, wheat, etc.), the green component G of the crop area is much greater than the red component R and the blue component B. Therefore, a 2G-R-B (ExG) filtering algorithm that emphasizes the green component and suppresses the remaining two components can be used to grayscale the color image (García-Santillán et al. 2018; Vidović et al. 2016; Arroyo et al. 2016). The existing navigation line extraction algorithm of the automatic navigation system based on machine vision is easily interfered by the external environment, and the processing speed is slow. To solve these problems, Zhai et al. (2016) proposed a multi-crop line detection algorithm based on binocular vision. Relying on this algorithm, color images of different crops were obtained, and the 2G-R-B algorithm was used to grayscale the color pictures for the acquisition of pictures with clear contrast between the crop rows and the soil background.

Zhang et al. (2014) proposed an online recognition method for apple defects and pedicel calyx based on brightness correction and AdaBoost. During Zhang's research, focused on Fuji Apple, first the RGB image and NIR image of apple were collected online, and the NIR image was segmented to obtain the binary mask of apples. Second, the brightness correction algorithm was used to perform brightness correction on the R component image, and the corrected image was segmented to obtain the defect candidate area (stalks, flowers, defects, etc.). Then using each candidate area as a mask, the information of the 7 pixels inside it were randomly extracted to represent the characteristics of the candidate area, and the seven groups of features were sent to the AdaBoost classifier for classification and voting. The category of the candidate area was determined using the final voting results. In order to study the distribution of cantaloupe surface texture features, Ma et al. (2014) collected a variety of cantaloupe sample images. Ma performed algebraic operations on the R, G, and B components of RGB color images, converted them into grayscale images, and then carried out background segmentation. The image was then decomposed using double tree complex wavelet transform (DT-CWT), high-frequency sub-images were obtained, and neighborhood operations were carried out. Furthermore, using iteration method, the optimal threshold was selected to complete the texture extraction. Finally, the gray difference statistical method and texture spectrum analysis method were used to describe and analyze the cantaloupe texture features, and a classification model based on support vector machine (SVM) is established. The research demonstrated that using the combination of DT-CWT and neighborhood operation, more continuous and complete cantaloupe texture images could be available. Additionally, it is noteworthy that the texture feature values of the four kinds of cantaloupe differ significantly, and the accuracy rate of classification using texture feature values reached 89.3%.

HSI Segmentation Model

Hue is a property that describes solid colors. Saturation gives a measure of the degree to which pure color is diluted by white light; while intensity, the most useful descriptor for monochrome images, can be measured and easily interpreted. The HSI (hue, saturation, intensity) color model conforms to the way people describe and interpret colors. This model can remove the influence of intensity components from the color information (hue and saturation) carried in a color image, making it more suitable for gray processing technology. HSI is an ideal tool for developing image processing methods based on color description.

The complex and changeable color of grape stalks and irregular contours make it difficult for the picking robot to accurately locate the picking points. To solve this problem, Luo et al. (2015) proposed a new method for picking point positioning based on improved clustering image segmentation and the minimum distance constraint of point and line.

Firstly, by analyzing the color space of grape images, the HSI color space component H that can best highlight summer black grapes is extracted, and an improved optimization method with artificial bee colony and fuzzy clustering was used to segment grape fruit images. Morphological de-noising processing is carried out on the segmented image, the largest connected area was extracted, and the centroid, contour extreme points, and circumscribed rectangles of the area were calculated. Then, the region of interest of the picking point was determined based on the centroid coordinates and information on the edge of grape cluster. Furthermore, the cumulative probability Hough straight line detection was performed in the area, and the distances between all the detected straight lines and the centroid were determined. Finally, the straight line with the smallest point-line distance was selected as the line where the picking point was located, and the coordinates of the midpoint of the line segment were used as the picking point.

Texture Segmentation Model

A large number of detailed information is contained in texture, and such information can be used to significantly improve image segmentation. In plateau pika target tracking, the target and background color are similar in natural habitats. To solve this problem, Chen et al. (2015) proposed a plateau pika target tracking method based on local texture difference operator. A new visual descriptor, named the local texture difference operator (LTDC), was constructed to reflect the subtle differences between the target and the background. The method demonstrated its strong capacity to distinguish target from background. Additionally, this descriptor can accurately locate the plateau pika target in scenes with similar target and background colors.

Forest vegetation is an important target in remote sensing image segmentation, and effectively determining the texture scale of forest vegetation is an essential aspect of texture segmentation. Liu and Yang (2015) proposed a method for describing the texture characteristics of forest vegetation in remote sensing images using the blue noise theory. This was a new method for vegetation texture characterization and texture scale calculation. In their research, the correspondence between the scale and the texture of the vegetation was studied. For the selected detection area, the blue noise characteristics were iteratively searched. The iterative process included reducing the size of the area by geometric transformation, using the fast Fourier transform to obtain the spectral response of the area, and extracting the blue noise features from the spectral response. For areas with blue noise characteristics, the gray distribution of the forest vegetation texture was calculated, and the size of the texture was calculated according to the current area size. The experiments they conducted demonstrated that the measurement results of the scale and gray distribution of the texture units of forest vegetation are accurate; thus a reliable basis was provided for further texture segmentation. Aiming at the current problem of multi-feature utilization in remote sensing image segmentation, Wu et al. (2013) proposed a segmentation method that makes comprehensive use of spectrum, texture, and shape information. The method, based on the initial segmentation, counts the spectrum and LBP texture features of the region; then calculates the heterogeneity between adjacent regions based on the spectrum, texture, and shape features; and uses this as a basis to construct a region adjacency map. Based on the adjacency graph, a stepwise iterative optimization algorithm is adopted to perform regional merge, thus acquiring the final segmentation result. It was demonstrated by the segmentation experiments of QuickBird and SAR images that the algorithm can make full use of the spectrum, texture, and shape information of the ground features in the image and that the effect and efficiency of segmentation are satisfactory.

8.3.7 Standardization of Agricultural Data

8.3.7.1 Overview of Agricultural Data Standardization

Information-based development is driving the transformation of agriculture from traditional to modern. Agricultural economy depends not only on traditional agricultural resources but also on the extent to which modern technology is used and to which information is obtained and used. Countries around the world are building various agriculture-related databases, data platforms, and agriculture-related websites based on relevant information to provide timely and comprehensive agricultural information services to producers and researchers. Agricultural information has developed rapidly. The huge amount of data has brought rich and comprehensive information to agricultural activities. At the same time, a number of problems have emerged, including disorder, distorted content, and reduced social benefits. As Nasbitt puts it: "Loss of control and unorganized information no longer constitutes a resource in the information society. Instead, it will become the enemy of information workers" (Zhang et al. 2011). How to reasonably organize, share, and use agricultural information resources has become a major problem. Technical solutions such as automatic crawling and intelligent search are not the best ways to use agricultural information, and standardization of agricultural information is the key to this problem.

8.3.7.2 Definition of Agricultural Data Standardization

Agricultural information is a wide-ranging subject, including multiple fields and levels of production, as well as agricultural economy, markets, policies, and regulations. The standardization of agricultural information refers to the standardized management of all links of agricultural activities and the connection of the different stages of the acquisition, transmission, storage, analysis, and utilization of information. Via such standardization, agricultural information can be reasonably used, and the scope of information sharing can be expanded.

It is generally believed that agricultural information standardization refers to the most common, most regular, and most repetitive things and concepts in the field of agricultural information technology. By formulating, publishing, and implementing standardization, agricultural information technology can achieve a certain unity or consistency within a given range. This unification or consistency is the prerequisite for the implementation and sharing of information resources, which facilitate the promotion and popularization of information technology. Furthermore, it will also be conducive to the development and utilization of agricultural resources and to the formation of information-based industries in agriculture.

8.3.7.3 Contents of Standardized Processing of Agricultural Data

Standardization will make agricultural information simple, practical, open, and easy to maintain, and the information standards will be made science-based and forward-looking. The standardization of agricultural information is manifested in improving the integrity, reliability, timeliness, and applicability of information acquisition and in achieving the accuracy, reliability, versatility, and effectiveness of information processing and utilization. Based on the above principles and objectives of standardization, agricultural information standards should include the following aspects.

Agricultural Data Terminology Standards
Through extensive inquiries of and reference to agricultural standards, the basic concepts of research on and management of agriculture are collected and sorted out, and the words with high frequencies of agricultural use are standardized and unified to ensure consistency of the terms. By revising and formulating new terms, the accuracy of information is guaranteed. Based on the principles of science-based measures, easy usage, and easy maintenance, an agricultural terminology database is established to provide an informative terminology set for producers, managers, and research and technical personnel.

Classification and Coding of Agricultural Information
According to the science-based, forward-looking, open, and easy-to-maintain principles of agricultural information standardization, agricultural information is rationally classified, and the attributes are standardized.

Agricultural Data Technology Standardization
China's agricultural departments at all levels have now developed many sets of expert systems, real-time control systems, geographic information systems, and model simulation systems. These systems are related to each other and are the sources of data for each other. But without a unified technical standard, exchanges between the systems are not possible, and resource sharing cannot be achieved. Thus, standardization is the foundation for the sharing and deep processing of agricultural information.

Agricultural Data Management Standardization
In addition to agricultural information, data management in agriculture must also be standardized, which is one of the prerequisites for ensuring the reliability of agricultural information. Standardization of data management includes standardization of the acquisition, processing, exchange, and release of data.

8.4 Multi-Source Agricultural Information Fusion Technology

Multi-source information fusion is an information processing method for systems using multiple types of information sources (or sensors). The information from multiple sources or multiple sensors is comprehensively processed to obtain more accurate and reliable conclusions. The technology is also known as multi-source correlation, multi-source synthesis, sensor integration, multi-source information fusion, multi-sensor information fusion, etc. This section introduces the concept, basic principles, and applications of multi-sensor data fusion in agriculture.

8.4.1 Concepts and Principles of Multi-Source Information Fusion Technology

Information fusion, a new multidisciplinary discipline, originated from the US Department of Defense's Sonar Signal Processing System Project in 1973. In the 1980s, multi-sensor data fusion technology was developed to meet military needs. In recent years, as agricultural IoT technology matures, multi-sensors have also begun to be used in agriculture to obtain multi-point information on agricultural products before, during, and after production, hence laying the foundation for multi-source agricultural information fusion.

Information fusion technology has grown rapidly, and a complete definition is not yet available. Information fusion technology refers to a process of information processing that uses computer technology to automatically analyze, optimize, and synthesize the information of several sensors obtained in time series under certain criteria, thus completing the required decision-making and estimation tasks.

In comparison with the comprehensive analysis in which the human brain rely on to obtain vision, hearing, taste, smell, and touch using the eyes, ears, mouth, nose, skin, and other organs, the basic principle of multi-source information fusion can be concluded as making full use of the advantages of common or joint processing of multiple sensors. Redundant information is eliminated according to certain criteria, and complementary information is synthesized to generate new effective information, thereby improving the effectiveness of the sensor system. This process is not limited to simple input and output; it is also the result of the interaction among various types of information. Sensors are the hardware foundation of multi-source information fusion, while coordination optimization and comprehensive processing are the core of multi-source information fusion.

Multi-source information fusion mainly consists of multi-sensor signal detection, data signal pre-processing, feature extraction, fusion calculation, and target recognition results. Among them, feature extraction and fusion calculation are the key links. More specifically, feature extraction means to extract target information that are useful for classification and recognition from the original data, whereas fusion calculation means to properly process the extracted target information for the completion of correlation, estimation, and recognition between the feature signal and the target parameters.

8.4.2 Algorithm and Model Fusion Technology

In practical applications, the state of an object is affected by multiple factors. The object is subject to its own properties and is also disturbed by a variety of external factors. Therefore, in actual applications, the state of the object is more complicated in space and time. Most algorithms and models are based on univariate time series, that is, only univariate time series information of a certain type of information source can be used, and existing multi-source information cannot be fully utilized. In order to solve the abovementioned problems, interactive multi-model, multi-algorithm technology, and multi-sensor information fusion technology could be combined to process multi-source information and extract comprehensive information that can best represent the state of the object.

In terms of algorithm fusion, such as multi-spectral and hyper-spectral image fusion algorithms based on three-dimensional distorted discrete wavelet transform, the same size is obtained by resampling, and three-dimensional distorted discrete wavelet transform is performed. Feature selection, a reasonable and effective fusion criterion, is adopted, the source image wavelet coefficients are combined, and finally the 3D inverse discrete wavelet transform is performed on the fused transform domain data to obtain a fused image.

8.4.3 Model Transfer Technology

Model transfer refers to mathematical methods applied to new sample states that empower models established under specific environmental or equipment conditions. Model transfer usually occurs between different instruments, different accessories of the same instrument, or different measurement environments.

With regard to objects with strong uncertainties, the following two main solutions have been proposed in terms of model transfer. The first is to establish parametric modeling of complex systems, and the second is to adopt multiple models to approximate the dynamic performance of the original system relying on the multi-model fusion. The former is primarily achieved through pre-processing, such as variable selection, differentiation, wavelet transform, multivariate scattering correction (MSC), standard orthogonal variable transform (SNV), Fourier transform (FT), and orthogonal signal correction (OSC). Moreover, extended correction models, robust regression methods, RPLS, INV-PLS, and other methods are tapped into for enhancing the selection capacity of the model built by the source machine, so that it can be used for the signal measured by the target machine. Yet it takes time to calculate the dynamic parameters of the model and to test the accuracy and adaptability of the model representation. Thus, there are only a limited number of such applications. In contrast, multi-model fusion, an effective method for solving complex modeling problems, is characterized by the linearized multi-model representation of a nonlinear system, and the uncertain parameter space (or model space) is mapped into a model set. The estimators work in parallel, and the results of each estimator are optimally fused to acquire the final estimate.

8.5 Summary

This chapter is mainly an introduction of information processing technology in agriculture. Starting from its basic concepts, characteristics, and types, the chapter outlines the key technologies in agricultural information processing technology, including data storage technology, data search technology, cloud computing technology, artificial neural network technology, geographic information system, image processing technology, and standardization of IoT and agricultural data. Based on this, the concepts and principles of multi-source agricultural information fusion and processing technology are laid out.

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Chapter 9
Agricultural Decision-Making Methods and Systems

Hui Fang, Fei Liu, Pengcheng Nie, and Jianjian Wu

Abstract Agricultural decision-making support system is a knowledge-enabled and computer-based system that supports and assists producers in decision-making. It is developed on the basis of agricultural information systems, agricultural simulation models, and agricultural expert systems. The system could assist decision-making with model combination and multiple scheme comparison. This chapter first analyzes the major problems in decision-making for production and discusses the decision-making methods and the development process of key technologies in the decision-making system. In addition, the typical agricultural decision-making support systems in each stage of production are introduced. In the future, the agricultural decision-making system will become modeled, precise, networked, and human-oriented.

Keywords Decision-making · Decision support system · Agricultural decision-making problems · Agricultural decision-making systems

9.1 Introduction

Decision-making refers to the strategy or method used to derive decisions. It is the process in which people formulate ideas and make decisions for various events. Decision-making is a complicated thinking operation process, encompassing information collection, processing, final judgment, and conclusion.

Decision support system (DSS) is a computer application system that helps decision-makers take semi-structured or unstructured decisions by means of human-computer interaction through data, models, and knowledge. It is a new type of computer information system for management that has become one of the most attractive

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application in the field of computer management. Essentially, the theoretical development of DSS relates to a number of disciplines, including computer software, information theory, artificial intelligence, economics, management science, behavioral science, etc. As computer software and hardware technology continue to mature, the range of computer applications has expanded from the initial numerical calculations to include a number of management areas.

DSS is also a scientific tool that assists decision-making in a specific form. It provides decision-makers with a working environment that combines knowledge, initiative, creativity, and information processing capabilities. Moreover, DSS is also an integration of qualitative and quantitative methods through human-machine dialogue. It assists decision-makers in analyzing problems, exploring decision methods, evaluating, forecasting, and selection.

Agricultural production, subject to regions, seasons, and cycles, involves a wide range of issues related to decision-making. Agricultural decision-making refers to the process in which people make choices or decisions on goals, plans, policy strategies, and major measures of agricultural production.

The agricultural decision support system is developed on the basis of agricultural information systems, crop simulation models, and agricultural expert systems. In addition to furthering development in agricultural information decision support system, agricultural production management decision support system, and agricultural intelligent decision support system, the international agricultural decision support system has expanded to include group decision support system and network decision support system, thanks to the development of information and network technology. Group decision support system aims at integrating decision support systems in different aspects of the same field or related fields to form a more comprehensive decision support system. The network decision support system, also known as a distributed decision support system, decomposes a decision task into several subtasks and distributes it on each node of the network to complete it. In the foreseeable future, the agricultural decision support system will become an indispensable decision-making tool for sustainable development in agriculture.

9.2 Analysis of Agricultural Decision-Making Problems

Agricultural decision-making mainly takes place during production. Generally speaking, the agricultural production process can be divided into crop farming, aquaculture, transportation, and processing. The content and focus of decision-making in different links have their own characteristics.

9.2.1 Crop Farming

The system of crop farming, an objective complex, was formed under certain natural, economic, technological, and historical conditions. Therefore, there are apparent regional differences in species, quantity, quality, distribution and regional combination of agricultural resources, and socioeconomic and technological conditions. Challenges for decision-making in different aspects of crop farming vary.

The first problem we encounter is the choice of plant varieties. For example, for the control and management of planting systems in larger areas, it is necessary to separate the areas with different characteristics and place similar areas into one category for classification and guidance. Such process of classification is the division of the planting system. To put it more bluntly, whether a certain area is suitable for planting a crop is subject to the combined effects of many factors, including socioeconomic, technological, and natural factors. Appropriate and case-specific arrangements must be made, i.e., land suitability evaluation must be carried out. Models are playing an increasingly important role in the evaluation of land suitability. This is the case because, firstly, traditional geographic information system (GIS) models may no longer adapt to the requirements of land suitability evaluation. Secondly, when it comes to the application of models, most of the systems still rely on the original GIS model, lacking the ability of mathematical modeling and spatial simulation required for land suitability evaluation (Xia et al. 2005).

In addition to evaluating the suitability of the land, it is also critical to determine the economics of the crops planted. Local resources ought to be fully tapped into, and public demands should likewise be met, so that more economic benefits could be delivered. At present, decision-making in agriculture is usually based on the experience of growers or experts. Such highly subjective decision-making always involves the biases of decision-makers, thus leading to deviations.

In the process of planting, growers need to make decisions for a variety of problems. For example, the core of making decisions for pest control is to determine the amount of pesticide spray in different areas of farmland on the basis of clarifying the types, occurrence degree, and changing trend of pests and diseases, and the difficulty in this process is to identify the types and extent of pests and diseases. The occurrence of diseases and pests is a complex natural phenomenon, which has global and regional characteristics in space, disordered instability and ordered periodicity in time, and other complex and changeable characteristics, such as heterogeneity, diversity, suddenness, randomness, migration, and regularity (Gu 2015). It is quite challenging to diagnose diseases and pests, predict the trend of diseases, and make the decision of control methods. The relationship between the factors of decision-making is not clear, and sometimes a bad decision may occur because of the lack of information. Decision support systems of diseases and pests that currently exists usually adopt traditional rule-based knowledge representation method against a specific disease. This method can be limited by knowledge acquisition and knowledge base maintenance. Furthermore, it usually uses a single reasoning method, such as case-based reasoning or rule-based reasoning, thus its reasoning efficiency is not obvious.

Another important decision that growers have to make is that of fertilization. Often times, growers attempt to determine the amount of fertilizer to be applied based on crop growth, environmental information, and their experiences. There are significant regional differences in agricultural production; therefore, soil nutrients in different fields drastically vary, and the rules of growth and planting and fertilization management methods of different crops also present individual differences.

9.2.2 Breeding

Commonly divided, breeding can be sorted into aquaculture and livestock farming. Similar to crop farming, aquaculture and livestock farming are also troubled by issues relating to decision-making about suitability, the economics of farming, and the production process. Compared with the crop farming, breeding often comes in two different production modes: family-based small-scale farming, and factory-based large-scale farming.

Family-based small-scale aquaculture production usually features scattered production sites, low levels of automation, unclear breeding rules, and lack of effective process management. Furthermore, management of aquaculture often depends on the experience of breeders to determine the breeding status for making the corresponding breeding decisions. Such conditions lead to high labor costs, failure to improve production efficiency, and high rates of operational error (Gao 2016), thus increasing the risk of breeding operations. Family-based small-scale livestock farming is usually dominated by free-range farming. The retail farming production equipment, production technology, and production conditions are relatively inferior, especially in terms of management philosophy; thus they are not able to meet the needs of modern aquaculture. Most farmers rely entirely on experience to make farming decisions on various issues. In addition, family-based small-scale farming often causes environmental pollution that includes air pollution, soil pollution, and water pollution.

A variety of advanced technologies is adopted in factory-based large-scale farming. For example, most researches on information-based aquaculture process management are focused on the detection of water temperature, water level, dissolved oxygen, pH, and other water quality environmental factors via relevant hardware equipment, aiming at establishing real-time monitoring systems for aquaculture, such as intelligent aquaculture based on the IoT control system (Li et al. 2013; Manju et al. 2017; Raju and Varma 2017), wireless sensor network-based aquaculture multi-environmental factor monitoring system (Shi et al. 2018; Tai et al. 2012; Yang et al. 2015), smart ecological aquaculture system (Li et al. 2017), etc. These systems help realize such functions as real-time monitoring and monitoring data analysis of aquaculture water quality. In addition, concerning Israel's highly intensive aquaculture model (Guan and Lai 2006), industrial circulating water welfare aquaculture industry model (Huang et al. 2013), pneumatic propeller-driven aquaculture automatic operation vessels (Sun et al. 2014), and industrialized aquaculture automatic feeders (Yeoh et al. 2010), they mostly rely on advanced aquaculture equipment to achieve automation in single or multiple aquaculture stages. These advanced information technologies and automation provide massive information for the generation of decisions, and some simple decisions can be completed directly. However, decision-making for some complex issues, such as the causes of diseases of different aquatic products, remains complicated. Large-scale livestock farming also involves the application of multiple advanced information and automation technologies. Today, livestock farming has evolved into a modern, scientific, large-scale, and intensive industry and has gradually shifted to the garden-type development, which completely overcomes the problems of air pollution, soil pollution, water pollution, and other common problems in the traditional small-scale farming. Modern livestock farming, in addition to placing a focus on the diseases of the livestock, has begun to involve the mental state and humanitarian issues of livestock and is able to establish new decision models based on new information technologies.

9.2.3 Transportation

Agricultural products go through several layers of links from field to consumers, among which transportation is an essential link. It can be divided into three aspects: decision-making related to transportation mode, decision-making related to logistics center, and decision-making related to transportation risk assessment.

9.2.3.1 Transportation Mode

Transportation mode decision-making is the first major part of transportation. Scientific and reasonable decision-making can avoid, to a certain extent, the loss that may occur during transportation and improve the trade quantity of agricultural products. Agricultural products are perishable and difficult to store due to their regional and seasonal characteristics; thus, transportation must be timely, fast, and economical. At present, there are three modes of transportation: road, railway, and waterway. Most carriers only engage in a certain type of transport function, and only a few carriers offer transport functions that coordinate with several modes of transport.

Transportation requirements for agricultural products are met depending on multiple factors. In terms of the evaluation of the selection principle of transportation mode, most scholars focus on the macroscopic perspective of goods transportation, but few on the selection principle of agricultural products transportation mode. Due to the short life cycle of most agricultural products, there are also unique requirements for the mode of transportation. Only by choosing an appropriate transportation method can agricultural products be transported economically, quickly, safely, and conveniently. The evaluation of transportation methods should include consideration on the impact of many factors. Firstly, the choice of transportation methods ought to follow economic principles. Secondly, it is necessary to improve the response capacity of transportation and to shorten the time and distance of transportation according to the specific features of products. Thirdly, the risk of transportation should be reduced, which is mainly reflected in avoiding wastes of goods. Based on studies of various factors and the characteristics of agricultural product transportation, the evaluation criteria for agricultural product transportation methods are determined, which are evident in three aspects: economic capacity, agility, and risk control (Guo and Xi 2015).

Although extensive studies have been carried out on supply chain-related issues under different channel right structures, there are few studies which consider both the attenuation law of product freshness and consumer price sensitivity and the optimal ordering decision of different transportation modes and different decision-making bodies in supply chains.

The existing researches mainly start from a certain restricting factor that affects the transportation of fresh agricultural products, and they lack the perspective of comprehensive research on the relationship between various influencing factors. The studies focus on the analysis of objective restricting factors rather than the psychological behaviors of decision-makers. In terms of influencing factors of transportation mode, empirical analysis is rarely used in existing literatures. Among the few quantitative models, behavioral principles and appeals of different transportation means are seldom considered and compared. Moreover, the influence of cost, time, and safety on the selection of transportation mode are not systematically discussed.

9.2.3.2 Location of Logistics Center

An appropriate location of logistics center can improve the overall efficiency of businesses, reduce the losses in the circulation process, and step up with the efficiency of distribution and transportation. With the development of modern science and technology, computer, mathematics, biology, and other related disciplines have been integrated into the study of location model of logistics centers, so that the depth and breadth of studies on the location of logistics centers could be enhanced.

Part of the existing decision-making system performs a purely quantitative analysis of location without giving consideration to subjective weights. Such methods often fail to consider multiple factors, resulting in decision-makings that are neither practical nor effective, whereas considering the qualitative factors of the site selection method and quantifying the qualitative factors can get better decision-makings.

Although there have been breakthroughs in studies on the impact of external conditions, it remains the case that the variable cost and the immutable cost are quite complicated to calculate due to the large number of influencing factors in the logistics center. The current research is still limited to the distribution between logistics centers and retailers, with the aim of finding suitable locations for logistics centers to minimize the total cost of transportation between logistics centers and retailers. Location issues between the manufacturers and the retailers have not been studied.

9.2.3.3 Transport Risk Assessment

Logistics businesses of fresh agricultural cold chain are rarely wholly information-based. Even if a node on the cold chain is information-based, it is difficult to ensure that it can be applied to the entire cold chain. Cold chain interruptions occur frequently and have become a bottleneck restricting the development of cold chain logistics.

Most of the transportation optimization problems center on how to choose the best transportation route, the best transportation method, and how to get the goods to the customer in the shortest time with the least transportation cost under the premise of known transportation tasks. However, the goal of a transportation company that makes profits by undertaking transportation tasks is to undertake those transportation tasks that can achieve the maximum profit among the many transportation tasks according to the actual business situation.

In terms of research on transportation reliability, there is currently no specific refinement of the reliability of fresh agricultural product transportation systems. Most studies only consider reliability as one of the elements of transportation, without separately refining all attributes that are correlated with the reliability of transportation systems. Hence, a complete concept of transportation reliability system is not possible. Therefore, there is a lack of discussion on the relationship between the performance constraints of the overall transportation system and decision-making for transportation mode. This is particularly true in relation to decision-making for transportation mode under transportation risk constraints. In terms of transport risks in logistics links, researchers focus on the risk analysis of the whole process of logistics (including other links of logistics) and enterprise transaction risks in supply chain risks, while the relationship between transport risks and risks in other logistics links is not fully explored.

9.2.4 Processing

Agricultural product processing is the sum total of industrial production activities based on agricultural materials, artificial breeding, or wild animal and plant resources. It is noteworthy that agricultural products classification and quality testing are important links.

In developed countries and regions, the quality classification of agricultural products is the key in agricultural administrative departments. The quality classification of agricultural products, the basis for the marketization of agricultural products, improves the efficiency of agricultural products markets and promotes agricultural modernization.

Based on machine vision, the fruit and vegetable quality detection and classification technology has yielded promising results. The indicators for detecting and grading the external quality of fruits and vegetables mainly include color, size, surface defects, shape, and texture. At present, the scope of various decision-making methods are relatively single, mostly focusing on fruits with similar appearance (Ying et al. 2000). The color, surface damage, size, shape, and various internal defects of fruits and vegetables play an extremely important role in their classification decision; hence, how to collect all-round information of products is vital in decision-making for the final classification.

In addition, the quality of agricultural products is difficult to classify due to factors that include region, time, and climate. The results, sizes, thicknesses, lengths, heights, fineness, leanness, and content of ingredients may differ even when it comes to products produced in the same variety, same region, and same season. Moreover, the quality of products varies significantly depending on the production technology deployed. Therefore, the classification and standardization of agricultural products is relatively difficult, and the grade and standard formulation come with obvious particularities, thus posing daunting challenges to the determination of decision-making methods for the final classification.

Though research on the application of machine vision in the field of agricultural product classification and grading is becoming increasingly extensive, there are still some deficiencies in the following areas: Many experimental studies are confined to the laboratory or static conditions; thus, it is difficult to put them into application. The range of agricultural products involved is not broad enough, and many agricultural products have not used machine vision to achieve classification. Computer vision technology is ideal when detecting a single index of food or using one index as the classification standard; however, if multiple indicators of the same food are used as the grading standard for testing and grading, the error of grading results ramps up, and the accuracy and time of testing fall below the ideal state. The detection adaptability is not strong, and the detection results are easily affected. Computer vision technology has a significant effect on the grading detection of a single kind of fruits and vegetables, but it is difficult to apply the same system and equipment to other kinds of fruits and vegetables. Moreover, sharing a set of computer vision equipment can be challenging even for the same type of different varieties of agricultural products. The current computer vision technology and supporting mathematical models are suitable for simple environments, while more errors may occur when working in complex environments.

The inspection of quality in processing holds great significance. Spectral technology has attracted the attention of many scholars because of its non-destructive features, short analysis time, zero pollution, low cost, and the fact that it does not require sample pretreatment. Although research based on spectroscopy has continued for a long time, similar problems related to the hierarchical application of machine vision exist. Let us take near-infrared spectroscopy as an example; the technology is easily affected by various factors (such as the temperature of the sample, the location of the sample, and the loading conditions). When the sample is moving, the near-infrared spectrum is more easily affected for online detection, and the acquisition of stable spectrum remains a problem. Most of the models used in online detection research are partial least-square method (PLS) or neural network models, which are abstract and undescriptive (Sun et al. 2009). The research on descriptive models and the application of descriptive models in online detection are not sufficient, most of which are only tentative; as a result, the detection model cannot be applied to agricultural products processing. Furthermore, the applicability is also limited because most models are for single agricultural products and designated spectrum acquisition equipment.

9.3 Decision-Making Methods

Decision-making, a purposeful thinking process of human beings, exists in all human activities and in the whole of human history. Since ancient times, human beings have altered their relationship with nature and society relying on their own unique decision-making capabilities in order to survive and develop.

Research on science-based decision-making began in the early twentieth century. After World War II, research on decision-making incorporated the results of behavioral science, systems theory, operations research, and computer science. By the 1960s, the discipline of decision-making, which specialized in researching and exploring the rules for making correct decisions, was formed. Among the relevant research programs, the prominent one is the modern decision-making theory proposed in the 1960s by the famous American economist and management scientist Herbert Alexander Simon, who pointed out that management is equivalent to decision-making (Simon 1977). Decision-making runs through the whole process of management that is actually composed of a series of decisions. The quality of decision-making plays a prominent role in the efficiency and effect of various functions of management. As research on decision theory and method furthers, decision-making is permeating into all fields, especially business undertakings.

In modern management science, decision-making is a conscious and selective action taken to achieve a predetermined goal. It can be treated as a process that involves asking questions, establishing goals, creating the design, and selecting solutions. Based on limited manpower, equipment, materials, technology, capital, and time, people put forward feasible schemes to achieve specific goals. A number of science-based methods and means are then adopted to compare, analyze, and evaluate the alternatives so as to obtain satisfactory results. The scheme will be modified according to the feedback of the plan until the goal is achieved. Scientific decision-making is the precondition that ensures the smooth progress of all kinds of undertakings, as well as a sign of leadership.

The extensive adoption of decision-making, and the diversity of human activities make decision-making diverse. According to the different conditions, decision-making can be divided into deterministic decision-making, risky decision-making, and uncertain decision-making.

Agricultural decision-making refers to the process in which people make choices or decisions on the development goals, discovery plans, action plans, policy strategies, and major measures of production. It generally includes strategic and tactical decisions, macro decisions and micro decisions, and group decisions of managers and individual decisions of producers.

9.3.1 Deterministic Decision Methods

In the decision-making process, several alternatives are proposed, each of which has only one result, so that the best choice can be made by comparing the results. A deterministic decision is a decision under a positive state. Decision-makers have a full understanding of the conditions, nature, and consequences of the problems relating to decision-making, and each alternative can only have one result. The key to this type of decision-making is to choose the best solution in a positive state. Common decision-making methods include differential analysis and cost-volume-profit analysis. The former is a method of selecting the optimal solution from the analysis of the differential income and the differential cost of each option by measuring the expected revenue and the expected cost of the two alternatives. The differential analysis also has certain limitations, in that it can only be used to choose between the two schemes. If the decision-maker is faced with three or more options, they can only seek alternative methods or use the differential analysis method to compare and finally select the best. The principle of differential analysis is simple, which is why it is widely used in production decision-making. The cost-volume-profit analysis aims to analyze the relationship between production cost, sales profit, and product quantity to grasp the law of profit and changes in loss and guide companies to determine a business plan that can produce the most products with the least cost and maximize profits. It can be used to calculate the breakeven point, also called the profit and loss divergence point and the income turning point, of the organization. The analysis principle is that when the output increases, the sales revenue increases in direct proportion without increasing the fixed cost. What is meant is that as the output increases, only the variable cost increases with it.

9.3.2 Uncertain Decision-Making Methods

In the process of decision-making with uncertain decision-making methods, various alternatives are proposed, each of which brings several different results, but the probability of occurrence in relation to each result cannot be determined in advance, so that the decision-making is uncertain. The difference between uncertain decision-making and risky decision-making is that in the latter, several possible outcomes are produced by each scheme, and their probability of occurrence are known, whereas uncertainty decision-making only offers the several possible outcomes produced by each scheme, with unknown probability of occurrence. This is the case due to insufficient understanding of the randomness rules of possible objective states of market demand, which increases the degree of uncertainty of decision-making.

The criteria of uncertain decision-making include pessimistic decision-making criteria, optimistic decision-making criteria, compromise decision criteria, regret-value decision criteria, and equal probability decision criteria. In the decision-making process, the selection of different plans depends largely on the experience, preference, judgment of natural state, psychological quality, attitude to risk, and other factors concerning the decision-making subject, hence making the decision-making process highly subjective. For the same decision-making problem, different decision-makers will adopt different decision-making criteria that correspond to different decision-making methods, leading to different decision-making results. Since there is no unified evaluation standard, we cannot determine the advantages and disadvantages of various decision-making methods. In order to better cope with the problems of uncertain decision-making, the decision-makers must conduct in-depth investigation and study, strive to improve their own quality, and accumulate decision-making experience extensively.

9.3.2.1 Criteria of Pessimistic Decision-Making

When dealing with uncertain decision-making problems, decision-makers may pursue foolproof decisions out of cautiousness. At this point, to be safe, we must assume the worst scenario, which is to say that one should first consider the worst results of each alternative, and then choose the best one among them, and draft the corresponding plan. That is, when the goal is to maximize the income, one ought to choose the plan with the largest profit value from the minimum income of each action plan as the decision plan, whereas when the goal is to minimize the loss, one should choose the plan with the lowest loss value from the maximum loss of each action plan as the decision plan.

The basic idea is to first calculate the minimum return value that various plans may have in their natural states and then choose the plan that corresponds to the largest value among these minimum return values as a decision plan.

9.3.2.2 Criteria of Optimistic Decision-Making

The criteria of optimistic decision-making require the decision-makers to adopt a sound and optimistic attitude – choosing the most satisfying decision plan when they are unable to determine the possible results of each plan. The basic idea of the code is that the decision-makers should always take an optimistic attitude toward the natural state of objective occurrence and hope that the most favorable state would occur with an optimistic spirit of adventure. For decision-makers aiming at maximization of benefits, they should first identify the maximum benefits of each scheme and then choose the scheme corresponding to the largest of the maximum benefits as the optimal scheme. Therefore, the optimistic decision criteria here is also called the maximum expected value decision criteria. Similarly, for decision-makers who aim at minimizing loss, the scheme corresponding to the one with the least loss should be selected as the optimal scheme from the minimum loss value of each scheme. The optimistic decision criteria here is also known as the minimum loss value decision criterion.

The basic idea is to first calculate the maximum possible benefits of various schemes in their natural states and then choose the scheme corresponding to the maximum benefits of these schemes as the decision scheme.

9.3.2.3 Criteria for Compromise Decision-Making

The guiding principle of this method is to seek steady development, meaning that decision-makers should be neither too optimistic nor too pessimistic and that a more stable plan is preferable. The specific steps of such decision-making are as follows: first, identify the minimum value and maximum value of each scheme in all states. Secondly, decision-makers should set the maximum coefficient a ($0 < a < 1$) according to their degree of risk preference, and the minimum coefficient is determined as 1-a. a, also known as the optimism factor, which is a measure determining the aversion to risks of policymakers. Then, the weighted average value of each scheme is calculated by the given optimism coefficient, and the corresponding maximum and minimum profit and loss value of each scheme are likewise determined. Finally, the scheme corresponding to the maximum profit and loss value of the weighted average is taken as the selected scheme.

9.3.2.4 Criteria for Minimum Regret Decision-Making

Ideally, decision-makers choose the solution with the largest gain or the smallest loss as the optimal solution. However, decision-makers may not take the optimal solution under ideal circumstances but adopt other solutions due to the influence of future uncertainty. Moreover, they would regret it if it were to be found that they missed the chance to reap the biggest rewards. Based on the idea of avoiding to regret in the future by choosing now, researchers put forward the criteria for regret decision-making, quantifying the subjective feeling of “regret,” and the value so determined is the basis for the decision.

This method uses the minimum value of the maximum regret value as the decision plan. The difference between the maximum return value in each natural state and the return value of each scheme is called the regret value, also known as opportunity loss.

9.3.2.5 Criteria for Equal Probability Decision-Making

When information about the emergence of future natural states is unclear, the criteria introduced in the previous sections make bold assumptions from different perspectives, hence simplifying the solution of uncertain decision problems. Viewed from the perspective of their respective starting points, all of them are justified, but their inherent shortcomings and limitations are also apparent. For instance, the criteria for pessimistic decision-making assume that the natural state that obtains the minimum benefit must occur, and the probabilities of other states are zero, whereas the idea of optimistic decision-making is exactly the opposite. The criteria for compromise decision-making introduce the concept of optimistic coefficient, which overcomes extreme thoughts but also only considers the best and worst natural state returns, assuming that the probability of other intermediate states occurring is zero. The common disadvantage of these criteria is that they do not make full use of all the information contained in the revenue function, which will significantly affect the accuracy of the decision. In the nineteenth century, Laplace, a well-known mathematician, proposed rules of equal probability decision-making, which overcomes the shortcomings of insufficient use of the above criteria. These criteria hold that when the probability of occurrence of each natural state is unclear, the probability of occurrence of each state can only be considered as equal. The expected return of each plan is obtained with equal probability, and the plan corresponding to the maximum expected return value is the optimal decision plan.

9.3.3 Methods for Decision-Making Under Risks

In the decision-making process of decision-making under risks, multiple alternatives are proposed, each of which has several different results, and the probability of their occurrence can also be calculated. The reason why decision-making under risk exists is that various market factors affecting the prediction target are complex and changeable, and the implementation result of each scheme is highly random. Therefore, no matter which action plan the decision-maker chooses, certain risks are inevitable. The main methods involved in decision-making under risks are revenue matrix method, decision tree method, and Bayesian decision method.

9.3.3.1 Payoff Matrix Method

The payoff matrix generally consists of three parts: feasible schemes, natural states and their probability of occurrence, and possible outcomes of various action schemes. The presentation of these three parts on a table is known as the return matrix. Decision-making under risks is based on the decision payoff matrix, which calculates the returns of each plan in different natural states and then calculates the expected return of each plan according to the weighted average of the objective probability, among which the best scheme is selected.

9.3.3.2 Decision Tree

As a diagram of the decision-making situation and a method commonly used in risky decision-making, a decision tree can be used to visualize the problems relating to decision-making. It draws various alternatives, possible natural states, and multiple profit and loss values on a chart. It is convenient for decision-makers to review the decision-making situation and analyze the decision-making process, especially for decision-makers who lack mathematical knowledge and are not sufficiently competent.

The criteria for decision-making under risk are expectations, which is an average of weighted properties in various states. The expected value of a scheme is the sum of the probabilities of its gains and losses in various states. The decision tree uses several branches to represent the expected value of various schemes, and if the branches with lower expected values cut out, the remaining scheme would be the optimal scheme. Decision tree consists of decision node, scheme branch, scheme node, probability branch, and result point.

Decision trees can be divided into single-stage decision trees and multistage decision trees. The former means that only one decision-making activity is required before an ideal solution can be selected. Single-stage decision trees generally have only one decision node. If the problem is more complicated and cannot be solved by one decision, and the most satisfactory solution can be selected through a series of interconnected decisions. This decision is called multistage decision. The goal of multistage decision-making is to optimize the overall effect of each decision.

When applying decision tree to decision-making, the following processes are usually involved:

- Drawing a decision tree. The given problem gradually expands from the decision point into scheme branch, state node, probability branch, and the result point. When drawing a decision tree, one should do it step by step (from left to right).
- Calculating expectations. The calculation of the expected value is performed gradually from right to left, that is, the expected value and the expected result of the scheme are determined according to the profit and loss value on the right side and the probability of the probability branch.
- Pruning plan. Based on the expected results of different schemes, the schemes with lower expected values are discarded successively from right to left and marked with symbols. This process can be figuratively called pruning. The last decision point leaves a branch, which is the optimal scheme.

When the problem only demand one decision, it is called a single-stage decision-making problem. If the problem is more complex and requires a series of decisions to resolve it, it is called a multistage decision problem. It is noteworthy that multistage decision problems are more intuitive and easier to operate using a decision tree decision method.

9.3.3.3 Bayesian Decision-Making Method

When dealing with risky decision-making problems, it is essential to determine the probabilities of various states. They are unconditional probabilities based on experience that are called prior probabilities. The method of expected value for decision-making chooses the best scheme according to the prior probability of various events. Such a decision carries certain risks because the prior probability is determined by historical data or subjective judgment and has not been tested in practice. In order to minimize this risk, we need to accurately determine and estimate these prior probabilities. It is critical to obtain accurate intelligence information through scientific experiments, surveys, statistics, and other methods to modify the prior probability, so that the posterior probability and the expected value of each scheme are determined, allowing decision-makers to make accurate choices.

The Bayesian formula gives the relationship between prior and posterior probabilities:

$$P\left(\theta_i|A\right)=\frac{P\left(A|\theta_i\right)P\left(\theta_i\right)}{\sum_{j=1}^{n}P\left(A|\theta_j\right)P\left(\theta_j\right)} \tag{9.1}$$

where $P(\theta_i)$ is the prior probability of event; $P(\theta_i|A)$ is the posterior probability of event θ_i; and A is any event and satisfies $P(A) \neq 0$. The basic steps of a Bayesian decision are as follows:

- Prior analysis: Decision analysts first collect supplementary statistical data and information, and apply state analysis methods to calculate and estimate the prior distribution of state variables in accordance with their own experience and judgment, and calculate the conditional results of each feasible solution under different natural states using this information. According to some decision-making criteria, the feasible solutions are evaluated and selected to find the most satisfactory solution, which is called pre-analysis. Due to objective conditions, such as time, human, material, and financial constraints, it is impossible to fully collect market information. Decision analysts can only complete the pre-analysis step.
- Pretest analysis: If the problem of decision-making is very important, and provided that time, manpower, financial resources, and material resources allow, it should be considered whether to conduct market research to supplement and collect new information. The basis of such consideration is to balance the benefit that supplementary information may bring and the cost of supplementary information. If the value of the information is higher than the cost, indicating that the advantages of supplementary information outweigh the disadvantages, it should

be supplemented. If the opposite is true, then supplementary information would not be unnecessary. This comparative analysis of the value and cost of supplementary information is called a pretest analysis. If the cost of obtaining the supplement is small or even negligible, this step can be omitted, and the investigation and collection of information can be directly carried out, and the next step based on the obtained supplementary information can proceed accordingly.

- Posterior analysis: After the pretest analysis, decision-makers make the decision relying on supplementary information and prepare for the post-test analysis by market research and analysis of supplementary information. The key to posterior analysis is to use supplementary information to modify the prior distribution, thus deriving a more realistic posterior distribution. Then, the posterior distribution is used for decision analysis to select the most satisfactory feasible plan. The value of information and the cost of comparative analysis are taken into consideration to make a reasonable explanation of the economic benefits of decision analysis. It is worth mentioning that both the posterior analysis and the pretest analysis use Bayesian formula to modify the prior distribution. The difference between them is that the latter is based on the possible investigation results, and focused on the judgment derived from supplementary information, while the former is based on the actual survey results, and focused on selecting the most satisfactory solution. In practice, the two are sometimes carried out simultaneously only with different emphasis because they are indistinguishable.

9.3.3.4 Agricultural Application of Decision-Making Under Risks

Agricultural production is an incompletely measurable activity that uses multiple natural and artificial inputs to obtain agricultural products. Owing to the randomness of the activity, there is the risk that it may not be possible to carry out crop production according to the ideal deterministic model, and the same is true for pest control, as the occurrence of pests shows a certain randomness. Implementation of a control measure, such as the layout of resistant varieties, naturally bears certain risks. In this case, it is necessary to scientifically estimate and quantify the risk probability and to identify the least risk prevention measures. This kind of quantitative method counts as decision-making under risks. At present, the dominant method of decision-making under risks for pest control is the Bayesian analysis. Zhang and Gu (1996) introduced multi-objective decision-making technology into the field of decision-making under risks and proposed a multi-objective decision-making algorithm and a comparative method to determine risk probability, hence providing research and application values in pest control decision-making. As IoT technology matures, agricultural decision support systems need to process increasingly diverse types of data. Combining various methods to improve the reliability of decision-making is a big data solution for modern agricultural decision support systems. The decision system designed by Guo (2018) enables real-time monitoring and perception of important parameters that include soil moisture, temperature, and light intensity in the agricultural production environment. This system adopts the Bayesian statistical inference to establish a multidimensional Gaussian statistical model of various indicators of smart agriculture. Based on machine learning, the decision threshold of environmental parameters is optimized, so that electrical equipment can be controlled more accurately and reasonably, and the goal of rational planting can be achieved. The system software platform features real-time monitoring and display of agricultural production environmental parameters, trend change of corresponding parameters, query and analysis of historical data, and map display and monitoring of greenhouse environmental parameters.

9.4 Decision Support System and Its Key Technologies

9.4.1 Decision Support System

Decision support system (DSS) was first proposed in 1971 by M. S. Scott Morton of the United States in an article titled *Management Decision System*. Essentially, DSS is developed at the basis of management information systems and management science (Cao 1997). Management information system is used to process a large amount of data and complete management tasks. Management science (or operations research) relies on models to aid decision-making. The decision support system combines a large amount of data with multiple models and supports decision-making through human-computer interaction. DSS is a human-computer interaction information system based on computer processing that can comprehensively utilize various data, information, knowledge, artificial intelligence, and model technologies. It can assist decision-makers at all levels to implement scientific decisions. Moreover, DSS comes with better flexibility and adaptability, quick responses, and a friendly, interactive user interface used to support the decision-making process. Though DSS may be helpful in solving semi-structured and unstructured decision-making problems, it cannot replace decision-making at higher levels.

The framework of the decision support system is shown below (Fig. 9.1):

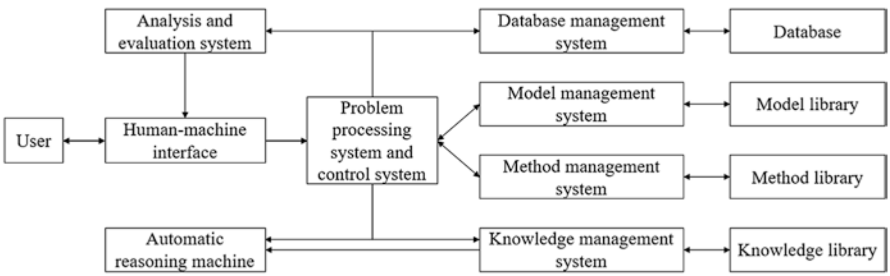

Fig. 9.1 The framework of the decision support system

- Human-machine interface: the bridge between the user and the system.
- Database system: storing the information needed to support decision-making. The data in the database has been properly processed and concentrated. In addition to the internal data of the enterprise, a large amount of external data is also required.
- Model library system: flexibly completing the storage and management functions of the model. Model library: storing various models used for decision-making, including strategic models, tactical models, operational models, and various model components and subroutines. Model library management system: responsible for the establishment and management of model library and model dictionary, model operation, model operation control, and interface management with database. Model dictionary: presenting the descriptive information about the model and data abstraction of the model.
- Method library system: a software system that provides algorithms for solving models. Method library: including methods and programs that make up various mathematical models, such as ranking algorithms, classification algorithms, minimum spanning tree algorithms, shortest path algorithms, linear programming, dynamic programming, various statistical algorithms, and so on. Method library management system: responsible for the establishment and management of methods, the building of the interface between method library and model library, and method dictionary management.
- Knowledge library system: solving semi-structured and unstructured problems. Including knowledge library, knowledge library management system, and reasoning machine. Knowledge library: storing various rules, causality, and experience of decision-makers. Reasoning machine: primarily responsible for selecting and implementing knowledge, and the common method used is searching method.

9.4.2 Key Technologies of Decision Support System

9.4.2.1 Data Warehouse

As market competition intensifies, and the needs of the information society rises, the quickly extraction of information from a large amount of data has become increasingly important. Doing so requires online services and a large amount of data for decision-making. Traditional database systems are complicated due to massive historical data. Plus, data of different systems is difficult to integrate, and the ability to access massive data is limited, thus traditional database systems are no longer able to meet market demands. In the early 1990s, the emergence of data warehouses solved these problems.

A data warehouse is a topic-oriented, integrated, stable, and different-time data collection used to support the decision-making process in business management. Data-oriented themes in a data warehouse correspond to traditional database-oriented applications. Topics are a standard for classifying data at higher levels, and each topic corresponds to a macro analysis area. The integration characteristics of the data warehouse means that data must be processed and integrated before entering the data warehouse, a key step in establishing a data warehouse. First, we must unify the contradictions in the original data and transition the original data structure from application-oriented to topic-oriented. The stability of the data warehouse refers to the fact that the data warehouse reflects the content of historical data, not the data generated daily. After the data is processed and integrated into the data warehouse, it is rarely modified. Additionally, the data warehouse is a collection of data at different times. It is required that the time limit of data storage in the data warehouse should meet the needs of decision analysis and the data in the data warehouse must indicate the historical period of the data.

The data warehouse cleans, extracts, and transforms a large amount of traditional database data used for transaction processing and reorganizes them according to the needs of decision-makers. Such highly concentrated data provides a useful basis of analysis for various decision-making needs.

9.4.2.2 Data Mining

Data mining technology is capable of the identification and extraction of hidden, unexplored information, knowledge and business models, and related factor association rules from a large amount of fuzzy, incomplete, and noisy random data.

Data mining technology involves many fields, such as database technology, data warehouse, fuzzy logic, artificial intelligence, statistics, machine learning, information retrieval, high-performance computing, visualization, and artificial neural networks. The scope of data mining encompasses structured databases, semi-structured hypertext files, and even unstructured multimedia data.

Data preparation, data collection, and interpretation evaluation constitute the three main components of general data mining. The data mining process, iterating in three stages, is shown in the figure below (Fig. 9.2).

The two basic goals of data mining are prediction and description. Prediction refers to using certain variables or several known fields in the database to predict unknown or future values of other variables or fields of interest, while description refers to finding understandable patterns that describe data.

Data mining methods include:

- Clustering: the data is divided into different classes, so that the data within the same class is as similar as possible and the difference between classes can be

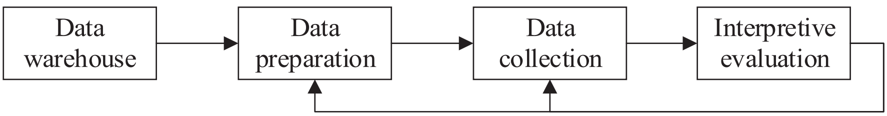

Fig. 9.2 The processing diagram of data mining

significant. The k-means algorithm is one of the most commonly used clustering algorithms. First, k objects are arbitrarily selected from n data objects as the initial clustering centers, and the remaining objects are assigned to the ones that are most similar to them according to their similarity (distance) with these clustering centers (represented by the cluster center). Then the cluster center (mean of all objects in the cluster) of each new cluster obtained is calculated, and this process is repeated until the standard measure function starts to converge.

- Artificial neural network: a mathematical or computational model that imitates the structure and function of a biological neural network (animal's central nervous system, especially the brain). It is used to estimate or approximate functions. Self-organizing map (SOM) or self-organizing feature map (SOFM) is a training sample space used to generate low-dimensional (usually two-dimensional) discretized representations using unsupervised learning. It is a method for reducing dimensions. Alkahtani et al. (2019) and others used SOM as a data mining tool to map high-dimensional distributions to regular low-dimensional grids in order to convert complex, nonlinear statistical relationships between high-dimensional data items into low-dimensional simple geometry relationships.
- Data visualization: data visualization integrates automated and visual analysis techniques to obtain visual knowledge from the data. Ellouzi et al. (2017) and others described the function of visual data mining as: in a decision support system, before applying visualization or automatic analysis, complex time data needs to be cleaned, preprocessed, and transformed. This data preparation is designed to export the appropriate temporal data representation for data mining.
- Classification: predicting which category a customer or event belongs to. The Bayesian method, based on the Bayesian principle, taps into probability statistics to classify the sample dataset. The feature of the Bayesian method is to combine the prior probability and the posterior probability, i.e., to avoid the subjective bias using only the prior probability. Moreover, the Bayesian method also avoids overfitting using sample information alone.
- Regression: regression analysis is based on a series of known or accessible correlations between independent and dependent variables to establish regression equations between variables. The regression equation is adopted as an algorithm model and used to connect the dependent variables on the new independent variable. Linear regression is the simplest and the most common used type of regression model. The data is modeled using a linear prediction function, and unknown model parameters are also estimated from the data. These models are called linear models.

9.4.2.3 Online Analytical Processing

Online analytical processing (OLAP) has rapidly developed in line with data warehouse technology. As an information analysis and processing process based on the data warehouse, OLAP is the user interface of the data warehouse. Data warehouses focus on storing and managing decision-oriented data, whereas OLAP focuses on data analysis in data warehouses and on transforming them into information to aid decision-making. When OLAP is used as a stand-alone application, sufficient data for analysis must be provided, and its data organization should correspond to that of the data warehouse. When combined with a data warehouse, OLAP draws data from the data warehouse. The large amount of data stored in data warehouse is organized in a multidimensional manner, which is the most suitable data organization method for OLAP.

OLAP technology is cross-sectoral and topic-oriented. Typical applications of the technology include slicing and dicing of multidimensional data, drilling, rotation, etc. Such applications facilitate users to extract relevant data from different angles. Another major feature of OLAP is the analysis of multidimensional data. Relying on OLAP, a mutual and complementary relationship with the multidimensional data organization of the data warehouse is formed.

The technical features of OLAP are as follows:

- Multidimensionality: Multidimensionality is the soul of OLAP. The system must provide multidimensional views and analysis of data analysis, including full support for hierarchical and multiple hierarchical dimensions. In fact, multidimensional analysis is the most effective way to analyze corporate data.
- Real-time response: Users expect strong response capabilities from OLAP. The system should be able to respond to most of the user's analysis requirements in a very short time.
- Targeting: The data in OLAP is prepared for the needs of decision analysis, thus eliminating the interference of a lot of redundant data that is not related to the subject.

9.4.2.4 Model Generation

Model generation refers to the establishment of a set of models in the system that can reflect the movement patterns of entities. This model is not necessarily a mathematical model, or it is not entirely a mathematical model.

The model generation process has four characteristics:

- The main storage mode of the model in the system is non-programmatic. Both data-based and knowledge-based model representations can be used as the basic form of the model. Of course, programmatic representation models may still be used in some areas.
- In the process of model generation, a combination of quantitative modeling and inference analysis is adopted. Quantitative modeling is used to determine the mathematical form and related parameters of the model, while inference analysis works before, during, and after modeling.

- The model is built via human-computer interaction. In the traditional modeling process, the boundary between the role of humans and the role of machines is clear-cut, but in the decision support system model generation technology, this boundary is ambiguous.
- Model generation should be a dynamic process. In particular, when the environment in which the entity is located changes, the environment in which the model is created should change accordingly. Even if the same steps are followed, the generated models will not be exactly the same.

The premise of model generation is that a simulation system of a solid environment must be constructed inside the system, which is called solid simulation environment. The simulation environment consists of two parts. One is a quantitative factor system, which is placed in the database, and the other is a non-quantitative factor system, which is placed in the knowledge base. It is obvious that the simulation environment cannot be independent of the usage context.

The model generation environment studied by the decision support system is not the specific content of the physical simulation environment; rather, this environment covers the conditions and software framework that should be included in the decision system in order to construct the simulation environment, which is called the framework environment of the model. There are five questions to consider when designing such a framework environment.

- Interactive mode: Natural language interface is an ideal way of interaction, and when it is not applicable, composite interface is often used instead.
- Model expression: When the model is expressed as a kind of knowledge, knowledge representation used to describe the model should be suitable for both quantitative calculations and inference analysis.
- Quantitative computing power: When determining the structure and parameters of the mathematical model, and when testing the generated model, a number of problems may occur in relation to quantitative calculation, most of which can be placed in the method library as subroutines. The algorithm as a subroutine should be independent of the specific application background.
- Reasoning analysis framework: Reasoning outside the context of the application struggles to go deeper. The framework generated as a model mainly refers to the basic structure of the inference system, the way of learning of knowledge, and the ability to acquire. If the designed decision system has a clearer background, the core knowledge embedded in the background would be able to bring great convenience to users.
- Management of the framework environment: Management function refers to the organization and coordination of the system. Powerful management functions are the key to the success of the system, especially when the system is actual use.

9.5 Typical Agricultural Decision-Making Systems

9.5.1 Suitability Evaluation Decision-Making System

In terms of crop suitability evaluation, many typical decision-making systems have been created. For instance, geographic information system (GIS), a basic platform for multidisciplinary integration of computers, geography, surveying, mapping, information, and management, can collect, store, manage, analyze, and display information related to geospatial space. Compared with traditional analysis methods, it transforms the past manual, single, static, and qualitative analysis methods into the multidimensional, multi-element, time-space integration, and qualitative and quantitative integration of comprehensive analysis technology. GIS has become one of the critical means of planning, environmental monitoring, and departmental decision-making in agriculture. The use of GIS technology for land suitability evaluation can make full use of existing data resources for comprehensive quantitative and qualitative analysis, achieve the systematization and automation of the land evaluation process, and provide accurate and reliable quantitative basis for land management and planning. Su et al. (2005) established a spatial analysis model of regional classification index based on three decades of climatological data and 1:250 000 basic geographical data from 90 meteorological stations in Guangxi, which provided the scientific basis for rational distribution of Shatian pomelo, seeking advantages and avoiding hazards and improving yield and quality of Shatian pomelo. Qiu et al. (2005) made comprehensive use of the "3S" technology to analyze and evaluate the suitable distribution status and utilization potential of fruit trees in Zhangzhou, Fujian Province. Yang et al. (2007) designed an ecological agriculture monitoring and decision support system based on WebGIS for tobacco planting in Honghe Prefecture, Yunnan Province. Cao et al. (2012) developed a precision corn planting decision-making system based on "3S" technology. The system provides accurate production information services for farmers and workers in the field of agricultural science and technology according to the basic situation of corn farming. In addition, it also features related functions such as query, modification, report, authority, and analysis of various related data. Qin (2018) chose 12 evaluation factors and soil management to construct a farmland suitability index evaluation system based on four aspects: soil nutrients, site conditions, and physical and chemical properties. A 16 m × 16 m grid was used as the evaluation unit, the analytic hierarchy process was used to determine the weight of the evaluation index, and remote sensing and geographic information system technology were used to establish a model for comprehensive evaluation. The suitability of cultivated land in the research area was divided into ten grades.

There are many more applications of this type of decision-making system. "3S" technology can be used to quickly and accurately obtain multidimensional information in agricultural production systems and manage and analyze spatial data. Global positioning system (GPS) can accurately locate the geographic location and review the results of agricultural zoning at fixed points to ensure that the results are true and reliable, while geographic information system (GIS) technology can simplify the processing and operation of data. The advantage of remote sensing (RS) technology is that it can quickly and accurately obtain information on the growth and environmental distribution of crops on the ground and identify non-agricultural land. The introduction of “3S” technology can provide a large amount of basic data and dynamic data for agricultural expert systems and offer data support for the establishment of expert system databases and model libraries, hence facilitating decision-making.

9.5.2 Cultivation Decision System

The rice cultivation simulation-optimization decision-making system (RCSODS) of the Jiangsu Academy of Agricultural Sciences in China combines rice simulation technology with the principles of rice cultivation optimization, so that the system is able to propose recommendations of decision-making for high-yield cultivation measures that correspond to different varieties and different environments. Each subsystem is based on the combination of the two models, and a decision model with strong mechanism and versatility is established for various cultivation measures. Moreover, the RCSODS system is not limited by the experience of regional experts. The system can effectively provide decision-making recommendations for measures of high-yield rice cultivation according to environmental conditions, such as climate and soil, and crop growth conditions, including previous crops, sowing dates, cultivation methods, and rice varieties. Therefore, the RCSODS system has a wide range of applications, and it clearly outperforms other agricultural decision-making systems based on expert systems.

The RSCODS system consists of more than 100 sets of mathematical models, which are mainly divided into two categories, the first of which are rice simulation models, including rice bell models, photosynthetic production models, stem borer dynamic models, nitrogen dynamic models, and yield formation models. Each model contains several sub-models. The second type is the rice cultivation optimization model, covering the best season model, the best leaf area dynamic model, the best stem borer dynamic model, the best yield model, the best fertilizer model, etc. The above models all use day as the simulation time unit.

The rice bell model includes four sub-models related to rice morphological development, namely, the development stage model, leaf age model, total leaf age model, and organ formation model. As the core of the RCSODS system, the development stage model features a time scale function, which controls the adjustment of the sub-models and corresponding parameters during the simulation of the entire system. At the same time, the formulation of various optimized cultivation decisions also serves a specific growth period. The fertility period model has successfully been applied, and it has further promoted the concept of fertility day in modern plant physiology. The model defines a diurnal cycle as a developmental physiological day under optimal temperature and light conditions and assumes that the number

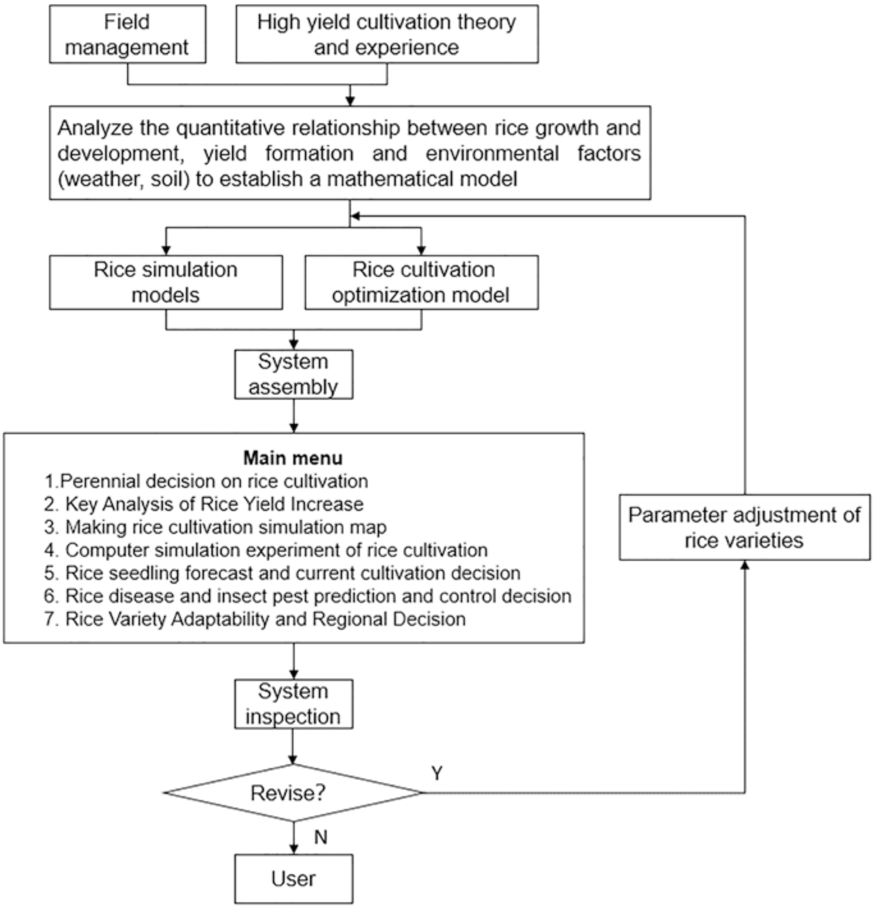

Fig. 9.3 The flowchart of RCSODS

of developmental physiological days required to complete a specific growth period is constant for a given rice variety. The proposal of the "constant physiological days" has been well-received globally. The main flowchart is shown below (Gao and Jin 1993) (Fig. 9.3).

The Expert System of Wheat Cultivation Management (ESWCM) of Beijing Academy of Agricultural and Forestry Sciences combines model technology and expert system technology. The organizational structure consists of natural and socioeconomic database systems (DBS), knowledge base systems (KBS), model base systems (MBS), inference engine (IE), human-machine interface (HMI), and system maintenance procedures. The system can make timely predictions on the growth and development of wheat and improve the ability of human foresight. When in use, decisions on the wheat field can be made block by block. According to the original production basis, environment and material input conditions, and management and scientific and technological level, the yield target can be formulated, the optimal combination can be determined according to local conditions, and the best plan for managing seedlings and decisions of classification guidance can be drafted. In order to improve the yield, adaptability and stability of crops, the appropriate varieties are recommended according to sowing time and different conditions of fertilizer and water; the appropriate sowing density is recommended according to the soil productivity and the sowing time of each point; the appropriate amount and method of fertilizer application are recommended based on soil fertility foundation and target yield; and the reasonable irrigation frequency, time and amount of water are recommended according to the seedling situation, soil moisture dynamics and conditions of weather and precipitation. ESWCM system can predict and actively regulate and control the population structure and ideal plant type of wheat to promote effective growth and to bring increase in effective accumulation. Relying on ESWCM, all links in wheat production are coordinated, and planned production is achieved (Zhao et al. 1997) (Fig. 9.4).

Developed by American scientists, the COMAX/GOSSYM cotton production management system, based on cotton growth models, and combined with cotton production expert knowledge, has been successfully used to provide guidance for cotton production management. The system consists of a knowledge base, an inference engine, a weather station, and a data file set (soil, variety parameters, weather data, agronomic measures, etc.). The growth model GOSSYM is essentially a model

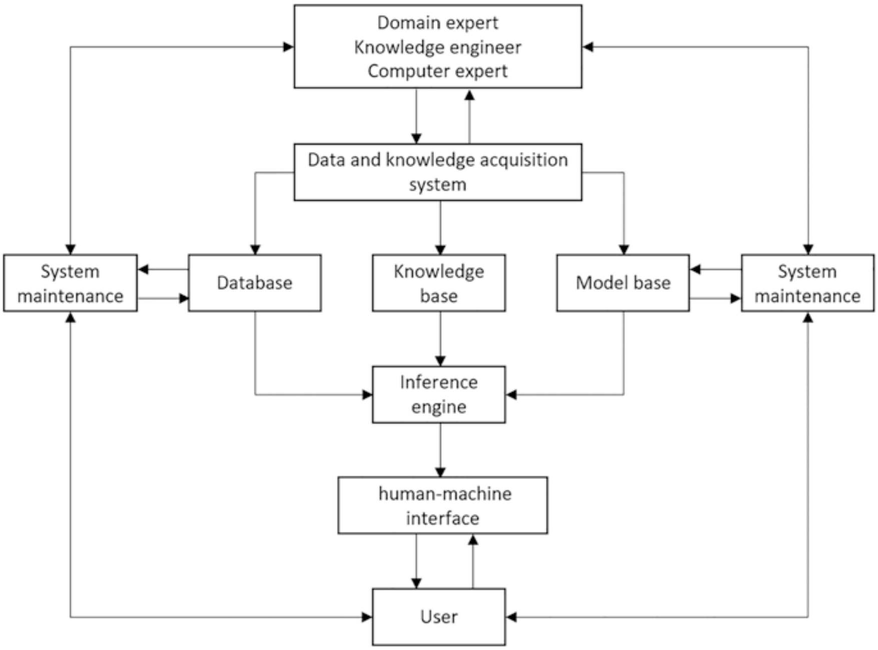

Fig. 9.4 General process of solving the organizational structure problem by ESWCM

that expresses the balance of water and nitrogen in the rhizosphere soil and that of carbon and nitrogen in the crop. During operation, soil physical properties, soil nutrients, and moisture are the initial conditions; meteorological elements such as solar radiation and maximum and minimum temperatures during the day and night are the driving variables; and key agronomic measures and nitrogen, irrigation, and spraying agents are control variables. As a result, the dynamics of cotton growth, photosynthesis, respiration, material production and distribution, root growth, and morphological establishment are simulated. Based on these outputs of the growth model, the expert system COMAX makes a decision plan on whether to implement management measures, including irrigation, fertilization, and use of growth regulators, and provides it to the GOSSYM model, so that it can continue the simulation process. Finally, the expected increase of yield is generated according to the decision plan. Compared with a single growth model or expert system, the system can obtain more accurate, comprehensive, and mechanistic information (Mckinion et al. 1989).

The DSSAT (Decision Support System for Agrotechnology Transfer) system, one of the most widely used crop models in the world, can simulate daily crop growth and development process and respond to many factors, including crop genetic characteristics, management measures, environment, nitrogen and water stress, pests and diseases, etc. It is mainly used for tests and analysis, yield forecast, risk assessment of production, and climate impact in agriculture. It is a comprehensive computer model jointly developed by the Florida State University, Georgia State University, Hawaii State University, Michigan State University, International Fertilizer Development Center, and other international science organizations. The format of the model simulation input and output variables is standardized. The system features simple operation, powerful functions, and wide application range. Its purpose is to accelerate the popularization of agricultural model technology and provide decision-making and countermeasures for the rational and effective use of agricultural and natural resources (Jones et al. 2003).

DSSAT simulates crop growth by days and describes the growth and development process in detail according to the growth period, including the process from germination to flowering, leaf emergence, flowering period, grain filling, physiological maturity, and harvest. Released in 1989, DSSAT v2.1 included only a few crop models. Following DSSAT v2.1, DSSAT v3.0 was released in 1994, DSSAT v3.1 was released in 1996, DSSAT v3.5 was released in 1998, and DSSAT v4.0 was released in 2005, with each version containing more crop models than the previous version. For example, the DSSAT v4.0 application based on Microsoft Windows provides a friendlier user interface and easier analysis. At the moment, DSSAT v4.0 is the most widely used, which includes 17 crop models and modules, covering zone, management, soil, meteorology, soil-plant-atmosphere, CROPGRO plant growth, CERES plant growth, SUBSTOR plant growth, and soil organic carbon modules based on the CENTURY model. The DSSATv4.5 trial version released in 2008 contains more than 25 different crop varieties: CERES series models of cereal crops, including CERES-Maize, CERES-Rice, CERES-Wheat, CERES-Barley, and so on; CROPGRO series models of legume crops, including soybean model

SOYGRO and peanut model PNUTGRO; non-legume crop series models that include tomato, bahia grass, etc.; potato model SUBSTOR-potato; cassava model CROPSIM-cassava; sunflower model OILCROP; and sugarcane model CANEGRO are also included in DSSAT. Knörzer et al. (2011) added a simple shading algorithm to DSSAT v4.5, so that the model can simulate the relay intercropping. Finally, different crop models are connected and classified, and they are named as different cropping systems model.

In recent years, agricultural IoT has been a focus in the field of agricultural science research. Based on the comprehensive acquisition of data relating to production, intelligent technologies are used to combine the relevant data, so that production can be more intelligent. In the new decision-making system for field crop growth, the data acquisition and the automatization of the model are significantly improved. Taking field crops as the target, Zhao (2015) realized the field crop growth perception and established a smart management platform based on the front-end hardware sensors of the IoTs, which took GIS technology, cloud service technology, data mining technology, and web system construction technology as the core. The system could provide a suitable cultivation plan through the distribution of soil nutrients in a region and monitor growth environment and crop growth in real time. It makes up for the shortcomings of traditional agricultural IoT platforms in field crop growth monitoring applications and provides stable IoT management platform software for smart management.

9.5.3 Pest and Disease Decision Support System

Diseases and pests, posing challenges for agricultural production, are one of the major factors restricting increase of yield, income, and efficiency. Pests and diseases are sudden, destructive, and uncertain. At present, chemical control is a critical way to control pests and diseases. However, problems such as excessive use of pesticides and improper spraying often occur when chemical control is adopted, resulting in the loss of medicinal solution, waste of resources, and environmental and food pollution and posing a threat to food safety. To reduce the frequency and intensity of diseases and pests in an economical and effective manner, ensure stable production and improve quality and efficiency and food safety; it is essential to formulate a comprehensive and appropriate prevention and control plan and take the necessary measures to forestall any damages. Furthermore, these measures ought to base on the premise of accurate detection and diagnosis of diseases and pests, complete prevention and control plan, and timely emergency control measures. Research should be conducted on the relevant theories and methods of decision support for pest control, so that an effective decision support system for pest prediction, diagnosis, and control can be established and decision support services for plant protection can then be provided. Doing so bears practical significance for reducing or even avoiding the outbreak of crop diseases and pests and for maintaining the sustainable and stable development of agricultural production.

As a research focus, crop disease and pest control decision support system has become one of the main methods of crop disease and pest control. In 1978, PLANT/ds, a soybean disease and pest diagnosis expert system, was developed at the University of Illinois. This is the earliest agricultural expert system. In 1996, the Cereal Forecast System was developed in Switzerland. One of the main functions of the system was to provide recommended spraying doses of fungicides for major wheat diseases. Based on software engineering principles and expert system technology, Shao et al. (2006), using the LUBAN model and JSP programming language, constructed an agricultural disease and pest diagnosis and treatment inference engine and developed a remote diagnosis and treatment expert system for vegetable pests and diseases in Beijing, named VPRDES. This system can be used for remote diagnosis and treatment, information query, and management of more than 140 kinds of common diseases and pests of vegetables in Beijing, thus playing a vital role in promoting the pollution-free control technology of diseases and pests of major vegetables in Beijing, facilitating rational drug use, and improving the safety of vegetable products. As machine learning rapidly matures, it has also been extensively used in the prediction of pests and diseases. Taking apple tree rot as an example, Jiang (2015) studied and analyzed the prediction model of BP neural network and wavelet network. Furthermore, a decision-making system was established for the prediction and control of apple tree diseases, and pests. The system can provide a way for users to understand the information of pests and diseases and offer decision support for the forecasting of pests and diseases, helping fruit farmers make timely preparations for prevention and control. Moreover, prevention and control programs can be formulated earlier based on the severity of the predicted epidemic, so that the economic losses can be reduced.

9.5.4 Fertilizer Decision Support System

Fertilization status is also a major factor affecting crop growth. In the past, farmers can only rely on experience when applying fertilizer. Hence, in the process of fertilization, the amount and proportion of fertilizer applied are not well controlled. People are satisfied with obtaining regional average yield, but they seldom consider the consequences of blind input to farmland, low fertilizer utilization rate, increased production cost, and environmental pollution caused by excessive fertilization. Fertilization decision-making system refers to a computer information system that scientifically assembles modern information technology and soil evaluation and crop fertilization theories. It integrates expert knowledge, sound research results, and quantitative fertilization models to assist soil nutrient evaluation management and recommendation for fertilization. The application of fertilization decision-making system can improve the legitimacy and accuracy of fertilization. To build the precise fertilization decision support system, the quantitative relationship between different growth and development stages of crops and soil, meteorology, and management measures ought to be studied, so that a theoretical basis for generating variable prescriptions at different scales can be provided. The crucial problem is the determination of the amount of fertilization, and the difficulty lies in the formulation of decision models.

During the research and development of fertilization technology, there have been frequent reports on various kinds of computerized fertilization systems, including rice, cotton, vegetables, and fruits. At present, mature fertilization systems include the sand ginger black soil wheat fertilization expert system developed by Anhui Institute of Artificial Intelligence, Chinese Academy of Sciences; the soil fertilizer test and agricultural statistics package developed by Soil and Fertilizer Institute of Chinese Academy of Agricultural Sciences; and the soil fertilizer information management system developed by Yang et al. (1994). Apart from these, a decision support system for soil information management and fertilization in Dafeng City, Jiangsu Province, was developed by the School of Resources and Environment of Nanjing Agricultural University. The Artificial Intelligence Research Center of Hebei Agricultural University has developed the GIS application in precision agriculture – variable fertilization intelligent spatial decision support system (VRF-SIDSS). Fang from Northeast Agricultural University designed an intelligent decision support system for soybeans in Heilongjiang Province. However, these decision-making systems are specifically designed for a certain region or a certain crop; thus, they are not universally applicable. Precision agriculture demands the development of a fertilization decision system that is universally applicable. Auburn University developed a recommended fertilization system with 52 crop fertilization standards, and the International Agrochemical Service Center of the United States has developed a fertilizer application recommendation software that can provide consultation service for n nutrient elements of 140 crops. Zhang et al. (2009), using remote sensing data, farmer survey information, and soil sampling point data, and combining them with expert fertilization knowledge models and Java language, developed and established a farmland management and fertilization decision support system on the WebGIS platform and realized visual management of farmland resources. Decision-makers can learn about farmland management and soil fertility status through the network platform and get expert recommendation fertilization guidance through this system. Ren et al. (2011) proposed a fertilization decision system that was built on knowledge base. Through the design of knowledge base as the interface between data and program, the organic integration between knowledge base and system is realized by relying on reasoning machine, and the localization customization and extension of system are achieved through the change and maintenance of knowledge base. The system features higher scalability and versatility and has been applied in many places in China.

The fundamental goal of fertilization is to make the crops grow better, the focus of farmers. Agricultural decision-making systems based on the growth model predict the growth and development of crops in advance and guide people in decision-making. Such systems have been widely studied and developed.

9.5.5 Aquaculture Decision Support System

Gao (2016) designed and implemented a set of aquaculture monitoring and management system based on IoT technology. Within this system, the bottom terminal device reports the status information to the supervision system through the Internet of Things. Producers can view the real-time status of the fish pond on the platform through the internet supervision system. Moreover, they are able to control the device switch according to the pond status and send instructions to the terminal through the supervision system. At the same time, the system also provides practical functions that include food feeding decision-making, remote disease diagnosis, and quality tracing, effectively improving the efficiency of aquaculture.

Qiao et al. (2015) summarized the feeding rules of fish and constructed an intelligent feeding system based on real-time machine vision decision-making in order to determine the feeding status of fish in real time and to control feeding relying on the system. The system collects and processes fish feeding images through real-time image processing technology. Plus, it extracts the position and quantity characteristic values of fish groups, obtains the feeding rules of fish groups, and establishes kinematics and dynamics models of actuators, including feeding and throwing of bait machines, hence achieving the intelligent control of bait throwing.

Chen et al. (2018) using the culture process of South American shrimp as an example, integrated the Activiti workflow engine and Drools rule engine into the Eclipse development environment and built an automatic aquaculture decision-making process management system based on workflow and rule engine. This system allows for all-round monitoring and management of the entire process of aquaculture operations, automatic decision-making, aquaculture environment, water quality, scientific feeding, disease control, and aquatic animal growth status, providing aquaculture experience and improving aquaculture benefits. The system reached the goal of processed, automated, and refined management of the whole aquaculture process.

The WIN-WEB mode cow SDSS designed by Lan (2008) combines a human-computer interface that comes with a web browsing function and a local decision-making function with a system interaction interface. Such design allows intelligent online analysis of historical data and data mining, so that the best problem solutions can be available. In addition, it can provide assistance for individual cattle farmers in breeding, feeding management, feed formulation, and disease treatment.

Chen and Jiang (2016), aiming at making production management of large-scale breeder farms more information-based, and improving the support for leadership production decision-making, built a system that supports fine farming of chickens. It also supports the intelligent production management system for farms with rational leadership decision-making. This system, based on the idea of "object-oriented," designed a flock production management module. Based on this, the data warehouse and data mining technology are used to design the production management and group production management modules. Additionally, SQL Server is used to analyze the decision data. The application of the system will standardize the breeding and management behavior of breeder farms and significantly improve the breeding benefits of breeder farms.

Liu et al. (2018b) constructed a new comprehensive decision support system, using data warehouse technology, to easily determine the specific form of the objective function according to the number of livestock, poultry, price, feed, and so on and to visualize it, thus providing reliable support for decision-making. At the same time, it also provides new ideas for solving the problems that traditional database systems cannot solve, such as the accuracy of original data extraction, regional differences, and variability of impact levels.

In the field of automatic feeding of cows, the Netherlands has developed a computer breeding management information system based on automatic identification of individual animal numbers. It features simulation and prediction of growth process, measurement of individual milk quantity, quantitative ingredients, monitoring of weight, health and physiological indicators, benefit evaluation, and growth rate control.

In Germany, electronic devices such as sensors are used to monitor the physiological parameters of dairy cows, and VB language is used to establish a data analysis system to analyze the changes in physiological parameters of dairy cows during lactation and estrus. A mathematical model was established using fuzzy logic mathematical methods as the mathematical theoretical basis for a computer monitoring system for estrus in dairy cows. The dairy estrus computer monitoring system, installed in the process computer that is connected to the data equipment, engages in the real-time monitoring of dairy estrus and makes timely and accurate dairy estrus forecasts (Xiong et al. 2004).

On the whole, the development of the farming decision support system is inseparable from the support of advanced information technology. Information acquisition technology has evolved from manual acquisition to automated acquisition. At the same time, the scope, accuracy, and quality of information acquisition have continued to improve, ensuring the accuracy and credibility of data obtained during the breeding process. Furthermore, the information processing methods in the breeding process are also moving toward modeling and intelligence. The application of computer technologies, ranging from data warehouse technology and online analysis processing to data mining and information processing, is more efficient, timely, and accurate than traditional decision support system processing methods.

9.5.6 Transportation Link Decision Support System

At present, living standards gradually improved as a result of rapid socioeconomic development, driving up the demand for agricultural products and the promotion of circulation scale. Agricultural products logistics, the service, and guarantee system for agricultural development, once encounter security problems, the whole system of agriculture would be inevitably affected, resulting in a huge impact on national economic stability and security. Therefore, the development and improvement of the decision-making system for the transportation of agricultural products is an important step to ensure the reasonable circulation of agricultural products.

The optimization of transport route is the most direct means to improve efficiency and ensure safety. At present, extensive research are conducted based on the optimal decision scheme of route. They take into consideration multiple factors in the actual situation to develop the decision-making system of agricultural products transportation. Gao (2011) developed a kind of agricultural product transportation system based on genetic algorithm. The system is designed as a B/S model based on the SOA architecture to adapt to the agricultural information system that changes with the needs and improve the availability and scalability of the system. The system features the integrated application of information acquisition and editing and intelligent information matching technology to achieve the entire-process operation of the source, processing, publishing, and application of information, thus ensuring the source of information and the availability of information. Aiming at addressing the shortcomings of simple genetic algorithm, such as insufficient convergence and weak local search ability, a new improved genetic algorithm (RGA) was proposed. Zhang et al. (2017) proposed a decision-making method for regional agricultural product distribution route that combines PM2.5 emissions and transportation distances. First, a routing decision-making model with the least PM2.5 emissions and the shortest transportation distance in the agricultural product distribution system is established. Then, an evolutionary algorithm based on similarity selection is proposed to facilitate decision-making in the regional agricultural product distribution route that combines PM2.5 emissions and transportation distances. This algorithm avoids the precocity of evolutionary algorithms and improves the diversity of the population. In light of the fact that some customers are in urgent need of supply during the distribution process, a virtual decision-making point is established to build a path decision-making model that meets the needs of these users. Finally, the validity of the proposed algorithm is verified using test cases, and a satisfaction index is given to measure the superiority of the algorithm. Xiao et al. (2008) studied the supply chain optimization and coordination of long-distance fresh products and designed a simple cost sharing mechanism. Kong and Li (2012) integrated GIS, wireless data transmission, wireless communication, and other information technology based on the characteristics of agricultural product logistics security and built a distributed emergency decision support system (DDSS) to reduce or even prevent such emergencies as agricultural product decay. Finally, based on GPS/GIS/SM (3G) technology, vehicle dispatching is taken as an example to illustrate the remote data collection and decision management implementation of typical functional areas.

In addition to optimizing the distribution route in the transportation of agricultural products, the appropriate location of logistics centers is also an important research direction. The appropriate location of agricultural product logistics centers can improve the efficiency of distribution and transportation, which, in turn, reduces the transportation time of agricultural products, improves the timeliness of transportation, provides better guarantee of product quality, and enables consumers to be assured of agricultural products, thus improving the safety of product consumption

(Fan 2010). The research of logistics center location theory can be divided into the following two categories:

- Quantitative analysis of site selection without subjective weight. Zhai et al. (2008) believed that the solution accuracy of the center of gravity method was poor and the distribution cost of the point was not the lowest. By comparing with the differential method, the optimal solution is obtained using the conjugate gradient method with fast convergence speed on the basis of using the centroid method to obtain the initial point. This method is mainly applicable to the study of the location of single distribution center. In the establishment of the model, only the relationship between transportation rates, transportation distance, and transportation volume was taken into account, and a certain fixed cost was not taken into account. Finally, the optimal solution was the coordinate value, and the coordinate point might be located in the middle of a lake or a street, so that practical significance might be possible. Wan et al. (2007), taking into consideration the actual planning problem of location, proposed the Dijkstra algorithm, the shortest path algorithm in graph theory, to build a logistics center location model. The algorithm can calculate the shortest distance between a specified node and other nodes in a logistics network. The main idea is to first find a path with the shortest distance from the source point and then obtain the shortest path from the source point to other target nodes by iterating the path distance. The disadvantage of this method is that only the shortest distance between nodes is considered, and the cost and time required by transportation between nodes are not considered.
- Consider the selection method of qualitative factors and quantify qualitative factors. Analytic hierarchy process can quantify qualitative factors. Some scholars have combined the methods of gravity center, goal planning, data envelopment, and other methods that involve the geographic location, cost, and supply capacity of logistics centers with analytic hierarchy processes, which have gradually improved the site selection method. Chen et al. (2005) first analyzed relevant data and information, including market demand, product characteristics, distribution status, geographical characteristics, and so on, then developed several alternative addresses using the center of gravity method, and finally determined the optimal solution using asymmetric analytic hierarchy process. This method combines the center of gravity method with the asymmetric analytic hierarchy process to select the location, so that the time required for decision-making is shorter. Zhang and He (2007) used the weights of fixed-cost investment, land area, throughput, number of logistics centers, and analytic hierarchy process as the constraints for goal planning. This method combines the objective planning method with the analytic hierarchy process and appropriately improves the analytic hierarchy process through matrix transformation, thereby omitting the process of consistency check. What is noteworthy is that this method is only applicable to the case where multiple logistics centers are selected when there are fewer resource constraints. When considering the service level of the logistics center, Nozick and Turnquist (2001) introduced a logistics location modeling

method in consideration of facility cost, inventory cost, transportation cost, and customer response speed and analyzed its operation mode. The inventory cost function is first embedded into a fixed facility location model, so that the optimal number and location of locations are directly related to inventory costs, and then the fixed facility location model is extended to multiple objectives, including cost minimization and coverage maximize, and finally this comprehensive model is applied to the logistics center location for a satisfactory location plan.

9.6 Development Trend of Agricultural Decision-Making Systems

9.6.1 Modeling and Precision

A high-quality expert decision-making system requires not only the accumulation of empirical knowledge but also the support of high-quality crop growth and development simulation models. From the simulation of physiological and ecological processes to information agriculture, the bridge in the middle is the crop model. The function of the model is mainly to understand, predict, and regulate the growth system of crops. The key to building such a model is basic research and field trials, the combination of which would lead to an effective crop model. Real-time control expert systems are widely used in Dutch vegetable and flower facility cultivation. The prerequisite for this is a systematic study of the relevant growth mechanisms of plants. Based on this, an agricultural expert decision-making system capable of simulating the expert level has been established (Liu et al. 2018a).

9.6.2 Comprehensiveness and Extensiveness

Natural conditions vary significantly between regions, therefore agricultural decision-making systems must be highly integrated and adaptable. A highly integrated agricultural decision-making system needs to make account of the influence of multiple factors and related knowledge bases and model bases. An agricultural decision-making system based on a particular topic will become a subsystem. Individual decision functions such as irrigation, fertilization, variety selection, pest and disease control, soil conservation, and environmental control will be incorporated into the crop production management decision-making system. Combining crop simulation models with agricultural expert knowledge to develop a comprehensive and functional agricultural expert system will be an important direction for the development of agricultural expert decision-making systems.

9.6.3 Openness and Extensibility

The agricultural decision-making system must be open and extensible. The system should be easy to upgrade, expand, and integrate, and the system should develop new technologies in synchronization with other technologies. The development of agricultural decision-making systems will unfold in the direction of dynamic data, high timeliness, and practicality, and it will become more intelligent as well. In addition, diversification of knowledge acquisition methods should be achieved, allowing authorized users to expand the knowledge base, so that the system can be equipped with self-learning and adaptive functions, and play the role of expert systems. At the same time, in such development, we must pay attention to the secondary and multiple development of the expert system, so that users can create their own knowledge base and model library according to local and individual conditions and expand the scope of application.

9.6.4 Interactivity and Usability

With the popularization of intelligent mobile terminals, in addition to emphasizing the combination with agricultural field models, deep knowledge, and common sense, agricultural decision-making systems integrate new technologies into expert systems and form a comprehensive system integrating multiple technologies, which is an important development direction. More mature technologies such as object-oriented technology and database technology can be considered and applied to expert decision-making systems. Such incorporation would allow the mutual penetration and integration between various disciplines. From physiological models to growth models, and to decision-making systems, work at different levels needs to be integrated. This process requires the cooperation of experts in different fields and the combination of different advantages to achieve breakthroughs. Global positioning system (GPS), geographic information system (GIS), and remote sensing (RS) technology are three major modern information technologies. They can quickly and accurately obtain multidimensional information in agricultural production systems and manage and analyze spatial data. The introduction of "3S" technology can provide a large amount of basic data and dynamic data for agricultural systems and provide data support for the establishment of system databases and model libraries. At the same time, multimedia technology, computer vision technology, virtual reality technology, and neural networks are becoming more mature. Applying these technologies to agricultural decision-making systems can make the system more human-oriented and easier to operate.

9.6.5 Networking and Human-Oriented Development

With the rapid development of computer networks and artificial intelligence, network information transmission has become fast and convenient. In the future, agricultural decision-making systems should consider networking the system. The data warehouse, model resources, and knowledge resources in the network environment all provide concurrent and shared model services and knowledge services on the network in the form of servers. Relying on big data technology, multiple data, such as soil, environment, water conservancy, and meteorology, can be clearly grasped, and the cultivation and sales of similar agricultural products can be better understood, thereby improving the accuracy and timeliness of decision-making, production efficiency, and resource utilization. On the basis of this, the model server can integrate a large number of mathematical models, data processing models, and human-computer interaction multimedia models to provide users with different types of model services, and it can also provide users with comprehensive services that combine multiple types of models. The knowledge server can centralize a knowledge base of multiple intelligent problems or knowledge of different knowledge representations (rule knowledge, predicate knowledge, framework knowledge, semantic network knowledge, etc.) and a variety of different inference engines, such as forward reasoning machine, reverse reasoning machine, hybrid reasoning machine, etc. Only agricultural decision-making systems that can successfully run on the network can be more practical and universal. Moreover, such systems can facilitate communication between farmers and experts and solve practical problems encountered by farmers in production.

The design and application of the system should also be human-centered. Most of the users of the system are farmers with limited professional knowledge. Complicated and visually unfavorable interactive interfaces are often unfriendly to farmers. If the decision-making system comes with a high threshold, it will not be universally applicable. Using graphical interface technology, integrated text, graphics, sound, and other multimedia technologies to visualize agricultural information allows users to understand agricultural information and decision-making technology information more clearly, hence making human-computer interaction more convenient and allowing users to accept and promote it.

9.7 Summary

This chapter first analyzes the typical decision-making problems in different fields of agriculture. Based on the introduction of typical decision-making methods, and taking typical agricultural problems in different fields as examples, the decision-making methods and key technologies are analyzed. Moreover, several typical decision support systems have been elucidated. Finally, the development of agricultural decision support system is illustrated.

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Chapter 10
IoT Management of Field Crops and Orchards

Pengcheng Nie, Qin Zhang, and Yong He

Abstract Fields and orchards are two of the main scenarios for agricultural IoT applications. One of the common challenges in these two scenarios is posed by the large farming area in open environment, and IoT-based management of field and orchard crop productions is an effective approach to cope with this challenge. This section serves as an outline of IoT management system of crops in fields and orchards. Moreover, an introduction is laid, describing the system's basic structure and the way in which it performs environmental monitoring, soil moisture monitoring, integrated water and fertilizer application, and pest and disease monitoring. The application of IoT for field crops and orchards can effectively reduce the impact of environmental and disease and pest factors on the growth of crops and fruit trees, minimize the use of fertilizer and water, and ensure the yield and quality of crops and fruits.

Keywords Field crops · Orchards · IoT management system · Application of IoT system

10.1 Introduction

The challenges facing the adoption of IoT system for the precision management of crop growth in open fields are primarily posed by the complex environment that requires high stability, accuracy, and service life of IoT systems.

The IoT system for field crops and orchards is used for farmland resource management, agricultural situation monitoring, precision agricultural operation, and

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agricultural machinery command and dispatching. Through collecting real-time information, the IoT system for field crops and orchards promptly controls the production process and establishes a high-quality, high-yield, and efficient management model to ensure the yield and quality of products (Li 2012).

Orchard IoT means the extensive adoption of modern sensor technology, information intelligent transmission technology, computer technology, and intelligent control technology in orchards. The information on soil, environment, growth, and meteorology in the orchard can be obtained in real time through sensors, and guidance for fruit tree growth and orchard management can be given after information processing. The introduction and application of the IoT technology to orchard information management can make orchards grow more information-based and intelligent, thus facilitating the building of a high-quality, high-yield, and efficient orchard production management mode.

Fields and orchards are defined by their large planting areas, the capricious climate, the significant environmental difference in different planting areas and the different soil characteristics. Focusing on the features of wide planting range, multiple monitoring points, complex wiring, and difficulties in providing power supply, IoT system uses high-precision sensors and information transmission control technology to collect soil information (moisture content, pH, nutrients), plant growth information (including nutrients and stress), and meteorological information. Through the combination of expert system and precise spraying of water and fertilizer, crop growth can be properly regulated.

Compared with the IoT for facility agriculture, the IoT system for field crop and orchard is more advanced and more demanding in terms of system stability, sensor service life, anti-interference ability, and signal processing ability. Moreover, this system can take into consideration regional differences and adapt to local conditions.

To provide readers with a comprehensive understanding of the application of IoT system for field agriculture, this section focuses on the introduction of soil moisture meteorological monitoring system, farmland environment monitoring system, management system of soil testing and formula fertilization, early warning system of field crop disease and insect diagnosis, and agricultural machinery scheduling management system and precision operation system.

This chapter focuses on the environmental monitoring system, field monitoring system, water and fertilizer integration system, disease and pest diagnosis and early warning system, and their application in field and orchard, so as to deepen the understanding of the IoT system for field crops and orchards.

10.2 Architecture of IoT Management System of Field Crops and Orchards

The IoT system of field crops and orchards are consistent with the IoT system for facility agriculture. Figure 10.1 illustrates that the IoT system for field crops and the IoT system for orchards share a similar architecture. The system consists of five

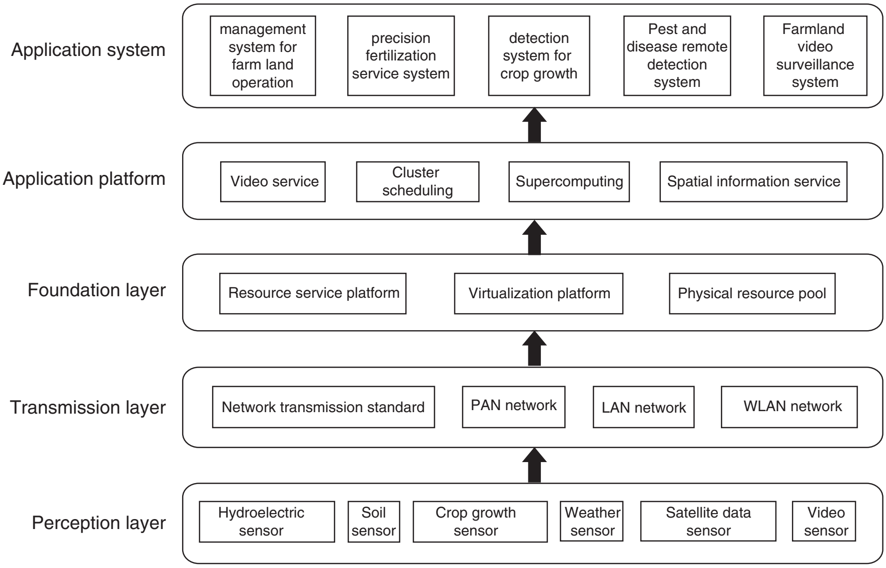

Fig. 10.1 Architecture of the IoT system for field agriculture

layers: perception layer, transmission layer, foundation layer, application platform, and application system.

The perception layer of the IoT system for field crops and orchards mainly includes sensors for the growth environment and climate information of soil, crops, or fruit trees. These sensors enable the perception of soil status, growth status, and climate information in the planting area in a scientific manner. The perception layer collects information for transmission, while providing feedback of the corresponding information when the IoT system commences with precision management of factors such as water and fertilizer supplement.

Major components of the transmission layer include information transmission among sensor nodes, wireless sensor network nodes, and control terminals. Concerning the planting area, wireless transmission is convenient and effective. There are two main types of wireless transmission: GPRS and CDMA (3G, 4G, 5G, and other wireless networks are also included). These transmissions, relying on network suppliers, feature wireless connection, simple installation, and strong mobility. Which is why they can be applied to scenarios where wiring and network distribution are not convenient. WLAN wireless network, equivalent to wireless network in a region, has advantages in terms of bandwidth and can be combined with communication networks. The transmission layer needs to ensure the stability of transmission, meaning that the transmitted information and commands ought to be complete and accurate.

The foundation layer, the basis for the application layer, mainly includes physical networks, resource service platforms, and virtualization platforms. The layer is used to provide the basic resources and information required by the application layer.

The application layer is primarily located in the control terminal. Based on the acquired information, it stores and analyzes the information on soil, growth of crops and fruit trees, and environmental and meteorological factors acquired by the perception layer. Through the expert system, and combined with big data processing technique, the layer enables the processing and feedback of the sensing information and the regulation of crops and fruit trees growth via the intelligent management system. More specifically, the application layer includes application platform and application system.

Based on the existing knowledge and models, and combined with the information obtained by the perception layer, the application platform is responsible for data processing, evaluation of growth status that supports decision-making, and the management and functional application of field agriculture, such as precise water and fertilizer irrigation, crop pest management, etc.

The primary role of the application system is to build IoT systems applied in different aspects, including management system for field crops and orchard operation, precision fertilization service system, and detection system for crop growth. Based on these systems, the IoT system for field crops and orchard is able to provide a wide range of functions (Li 2012).

10.3 Application of IoT System for Field Crops and Orchards

10.3.1 Environment Monitoring System and Its Application

The environment monitoring system of field crops and orchards is focused on automatic monitoring and intelligent transmission of information such as light, temperature, humidity, CO_2, micro-meteorology, and water quality. The monitoring system is mainly composed of various sensors distributed in different areas or various farmland environmental monitoring stations that contain different sensors, including microclimate monitoring station and hydrology and water quality monitoring station. According to the actual needs of environmental monitoring, different environmental monitoring stations carry different sensors. The information acquired by the monitoring station is transmitted to the terminal through the wireless transmission network and then processed by the application layer. Additionally, the monitoring station features low power consumption and integrated design. The station adopts solar energy as its power source and comes with outstanding tolerance for farmland environment and a certain degree of anti-theft (Wang 2018; Yao et al. 2011).

Let us take the construction of monitoring system for farmland meteorology as an example (the process and function of the environment monitoring of fields and orchards are also expounded). The monitoring system for farmland meteorology mainly consists of three parts. The first part is the meteorological information collection system, which is used to collect meteorological information. The meteorological information collection system includes sensors for rain, air temperature, air humidity, wind speed and direction, soil temperature and light, etc. As for the data transmission system, the function of wireless transmission module is mainly to transmit the collected data to the connected users or terminal application layer, in order to achieve remote transmission. The executive equipment can manage and control the system. Execution equipment refers to various facilities used to adjust the field microclimate change, including irrigation equipment and lighting regulation equipment. Control equipment refers to the data acquisition module that controls the data acquisition equipment and allows the equipment to function. Its main function is to control the operation status of the data acquisition equipment through the setting of the intelligent weather station system. According to the instructions issued by the intelligent weather station system, it can control the opening/closing of the execution equipment at any time (Li 2012). Figure 10.2 offers an illustration of the service platform of agricultural IoT.

Essentially, the monitoring system for orchard environment is consistent with that for the farmland environment. The monitoring system for orchard environment is primarily responsible for the automatic acquisition and remote communication of soil temperature and humidity, air temperature and humidity, and weather and water quality information. In addition, the acquired environmental indicators are transmitted from the monitoring station to the terminal. In the monitoring system for orchard environment, sensors can be distributed separately or integrated in the environmental monitoring station. The monitoring system for orchard environment includes data acquisition system and data transmission system. The data transmission system

Fig. 10.2 Monitoring system for farmland meteorology

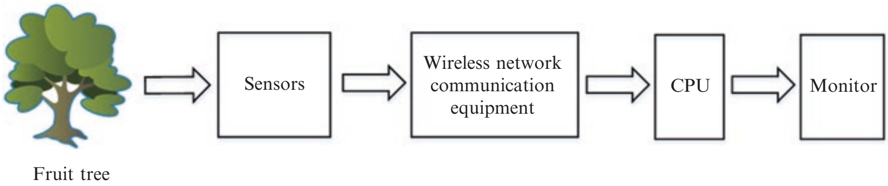

Fig. 10.3 Schematic diagram of orchard environmental monitoring system

is composed of two modules: wireless sensor network and remote data transmission. The sensor covers the whole orchard, and the wireless sensor network collects the scattered data and transmits them to the application layer using the wireless transmission network. Figure 10.3 shows the schematic diagram of orchard environmental monitoring system.

10.3.2 Monitoring System for Soil Moisture

Water is an essential resource in the growth of crops and fruit trees, while soil moisture is directly related to production capacity. Precision management of the moisture required for crops and fruit trees growth is of major significance for improving the yield and quality of crops and fruits. Against such a backdrop, IoT technology is applied to achieve the detection of soil moisture and nutrients in the field and orchard, the real-time decision-making based on soil conditions, and accurate regulation that guides the production process. The IoT monitoring system for soil moisture in field and that for soil moisture in orchard is consistent. The monitoring system for soil moisture achieves the diagnosis and early warning for soil and moisture in the following steps: first, the monitoring system obtains information (such as soil moisture content) in real time through the detection sensor. Then, it transmits the acquired information to the network node and the application layer through the wireless transmission network. To realize the diagnosis and early warning of soil and moisture, the system combines the information on meteorology, environment, and growth obtained by the sensors and taps into the diagnosis model and expert system. At last, the application layer uses intelligent control technique to remotely control the opening and closing of irrigation machine wells, canal gates, and other equipment through the service system for water management and also through the field irrigation system based on the diagnostic and early-warning information. In addition, the sensor of soil and moisture provides real-time feedback on soil moisture to control water consumption. In this way, the water consumption is controlled, the level of irrigation automation is improved, a suitable water environment is provided for the growth of field crops and fruit trees, and water resources are saved, while ensuring normal growth.

10.3.3 Integrated Application of Water and Fertilizer

The integrated management technology of water and fertilizer is a technology used to prepare soluble fertilizers into water mixtures according to growth and nutrient status. Apart from this, the technology could also accurately deliver the needed water and nutrients to the surrounding roots for their absorption and utilization with the help of irrigation system.

Compared with the traditional modes of irrigation and fertilization, integrated management of water and fertilizer has accomplished the transformation from channel irrigation to pipeline irrigation, from excessive fertilization to precision fertilization, and from separate irrigation and fertilization to water and fertilizer integration. It plays a major role in protecting ecological balance and achieving sustainable development of agriculture.

Relying on the monitoring system for soil and moisture, effective water management can be carried. The creation of a fertilizer requires the measurement of soil fertility. More specifically, the core of formula fertilization is to adjust and resolve the contradiction between the fertilizer requirements and soil supply. To improve fertilizer utilization rate, reduce the use amount, increase crop yield, optimize the quality of agricultural products, save labor and costs, and bring greater economic benefits, the elements required are supplemented in a targeted manner to achieve a balanced supply of various nutrients and to meet the needs of crops at the same time. The regulation of the proportions of various components in fertilizers is based on data derived from soil tests and fertilizer field tests. On the basis of reasonable application of organic fertilizer, the quantity, application period, and application method of nitrogen, phosphorus, potassium, medium and trace elements, and other fertilizers are determined according to the law of crop fertilizer demand and the performance and the effects of soil fertilizer.

Relying on the management system of soil testing and formula fertilization, the formulation of fertilization formula can be derived. This system, a software service system with strong functions, generates reasonable fertilization plans based on the key points of soil testing and formula fertilization. The system fully enables the management and application of soil measuring. It is divided into two large subsystems, a management system of soil data, and an application system of soil data. The management system, mainly used by specialists on agricultural technology at fertilizer station, is a maintenance management system for soil measurement data and basic information. It mainly includes functions of expert management, soil data management, fertilizer formula management, fertilizer management, fertilizer formula analysis, knowledge about fertilizer formula management, agricultural supply station management, and questionnaire management. The application system of soil data, mainly used to serve community-level agricultural production, is a platform for soil data application, fertilization formula application, and fertilization formula evaluation. It is also a platform for basic learning of fertilization formula. Its primary functions include query for soil data, fertilization formula, material supply, soil testing and formula fertilization technology, video face-to-face, and feedback on fertilization formula recommendation (Hu et al. 2015).

At the present stage, the integrated management technology of water and fertilizer based on IoT is combined with sensor technology, wireless transmission, intelligent systems, and other technologies. Sensors are used to quickly obtain information of crop, soil, meteorology, etc. Data transmission and management are then realized by IoT technology and an expert system or artificial intelligence, establishing an evaluation model of the demand for water and fertilizer to achieve a fully automated integrated management system of water and fertilizer. The integration of water and fertilizer can improve the utilization of water resources and fertilizers, increase the utilization of farmland, improve work efficiency, save resources, protect the environment, and ramp up yield.

10.3.4 Diagnosis and Early Warning System of Diseases and Pests

As common threats in the growth of field crops and fruit trees, diseases and pests have a great impact on the yield of crops and fruit trees. If not controlled, diseases and pests will occur and spread on a large scale. Severe diseases and pests will lead to large reductions in yields. Therefore, scientific monitoring, prediction, and prevention of diseases and pests are essential to the normal growth of crops and fruit trees.

There are many ways to diagnose and prevent diseases, but they often have little effect because of their unscientific and unsystematic nature. Therefore, it is of great significance to establish the IoT system for disease diagnosis and early warning, which includes five levels: perception layer, transmission layer, basic layer, application platform, and application system. Among them, the sensing layer is the key to obtaining information on diseases of crops or fruit trees. It integrates data acquisition, image acquisition, and information processing functions, and connects multiple disease detection and reporting sensors in series to monitor the environment and disease status in real time. In addition, when the IoT system starts with the precision management or other operations, the perception layer can be used to provide the corresponding feedback information and assist users to adopt the correct methods to prevent and control diseases. Generally speaking, disease detection and prediction instruments mainly refer to sensors used for crop information perception in the field, including RGB imaging, spectrometer, infrared thermal imaging, hyperspectral imaging (Cen et al. 2017; Zhao et al. 2016), and chlorophyll fluorescence imaging (Weng et al. 2018). These instruments can achieve high-throughput, full-automatic, and digital detection for different organs of crops and fruit trees. According to the corresponding measurement standards of the disease, the abnormal IoT monitoring signals obtained are analyzed through a series of data or image processing. The relevant information, such as the type and severity of the disease, are transmitted back through the transmission layer and the base layer, so that the IoT system can start the response mechanism for diseases. Aiming at improving the disease response mechanism, control measures are taken in the application platform and application system to realize the IoT diagnosis and early warning of crops and fruit trees diseases. At the same time, the expert system, featuring online remote video consultation and Q&A, can provide full technical guidance and services for production entities. The expert system, connected with smart agricultural clients, provides disease management knowledge to customers through smartphones or smart terminals. Furthermore, the disease diagnosis and early warning system can be used for remote diagnosis and consultation of common diseases and pests of crops and fruit trees, offering corresponding management measures.

Advantages of the IoT system for disease diagnosis and early warning of crops and fruit trees can be presented as follows:

Firstly, the system is equipped with an efficient and outstanding disease monitoring and identification system, which can automatically identify the type and degree of disease.

Secondly, wireless transmission technique can be used to establish collection points of disease information according to different crops in the monitoring range, so as to facilitate the automatic collection of monitoring data and the remote transmission of wireless network. The real-time reappearance can monitor the trend of disease occurrence in the field at any time when it is not in the field, effectively improving the promptness and accuracy of prediction.

Thirdly, multiple release methods can be adopted to send notification to farmers and guide them to carry out scientific and effective prevention and control.

Fourth, follow-up monitoring is undertaken on diseased objects, recording the disease occurrence dynamics, prevention and control situation, degree of loss, etc. The relevant records are then sent back to the decision-making side in a timely manner.

Pests constitute one of the major contributing factors for reductions in yield. Throughout their life cycle, pests often turn into large-scale and severe biological infestations, depriving large areas of crops of their normal physiological functions. In this context, scientific monitoring and prediction of pests and prior prevention and control are essential to reducing the impact of pests on the yield and quality of crops and fruits. Though manual monitoring and application of chemical pesticides is the most important method of pest control, it brings such problems as insufficient recognition of pests, pesticide residues, and environmental pollution. Thanks to IoT technology, field monitoring can be replaced with real-time monitoring of IoT devices, hence ensuring effective and real-time monitoring and reducing labor intensity.

Pests are unavoidable hazards to crops during their growth. The real-time monitoring of pests can be divided into three parts: the monitoring and sensing layer, the transmission network layer, and the application management layer. The monitoring and sensing layer, the bottom layer of the system, is mainly responsible for monitoring the pest status and real-time collection of relevant information. The transmission network layer transmits the acquired information to the application management layer through a specific protocol and then processes, stores, and makes the final decision (Heamin et al. 2017; Potamitis et al. 2017).

For field crops, remote photo-type pest monitoring light, wireless remote automatic weather monitoring station, and remote video monitoring system can be used as the collection terminal of the monitoring and sensing layer, obtaining the pest information, field epidemic situation, and environmental data in real time. Machine vision technique is a technique used to obtain the information of pests, and the IoT pest monitoring system based on machine vision technique is also a focus in related research (Han 2014). The collection status of pest images holds the key to subsequent monitoring and analysis. Therefore, the design of image collection system and image acquisition is critical. Industrial cameras generally use CCD or CMOS image sensors (depending on the actual needs). Based on the camera to collect the image of pests, an effective image segmentation algorithm is applied to segment the target and background of pests. According to the characteristics of the target area, the identification model of pests is established to engage in the environmental monitoring of farmland and the species identification of pests. Image segmentation and feature extraction are relied on to understand and analyze the acquired target image for better application. Commonly used segmentation algorithms include edge detection image segmentation algorithm and region-based segmentation algorithm, whereas feature extraction includes color, texture, geometry, etc. When there is a large number of identified species and pests, there will be interspecific similarity, intraspecific diversity, or attitude change among pest populations, which will further complicate data. In machine learning, an effective method to deal with large numbers of data, convolutional neural network can have direct access to data, thus constructing the layer-by-layer expression relationship between "image pixels – underlying features – high-level abstraction – final category," accurately detecting the information related to perception and improving the classification capacity of visual patterns (Liu 2017). The pest monitoring system based on IoT can improve the real-time monitoring and identification ability of field pests and provide accurate information for pest control.

IoT of pest diagnosis and early warning for fruit trees is similar to that for field crops. The pest monitoring system of orchard IoT monitors the growth and pest of fruit trees with the help of images and multi-channel videos. Once problems are identified, measures will be taken right after. The layout of insect collecting nodes plays an important role in the efficient operation of the system. This requires pre-assessment of the characteristics of the pests that occur, and the nodes are then distributed accordingly. For example, the information collection node may have a distant view node and a near view node. The former uses a rotatable and zoomable camera device to observe the growth of fruit trees in a wide range, whereas the latter uses a high-macro camera device to observe the specific situation of pests in the fruit trees. This solves, to a certain extent, the problems of low accuracy, poor timeliness, and high labor intensity of manual monitoring. Based on the analysis of the acquired information on insects, the trend of orchard insects can be predicted and forecasted, and the information on the changes of orchard insect conditions can be grasped at regular intervals as needed (Heamin et al. 2017; Potamitis et al. 2017).

The information of pests is transmitted wirelessly to the system model and then combined with cloud computing analysis to determine pest management decisions and behaviors.

The application of the IoT system has enabled disease and pest monitoring in fields and orchards. It proves to be laborsaving, real time, efficient, and accurate, addressing the problems of low accuracy, poor timeliness, low utilization rate, large collective labor intensity, and unintuitive performance with manual monitoring in the past. IoT systems provide major technical guarantee for the production and development of fields and orchards.

10.4 Examples of Application Systems

The Wangbuliao Citrus Specialized Cooperative in Yongquan Town, Linhai, Taizhou, Zhejiang Province, and Zhejiang University have jointly built the first intelligent IoT precision monitoring system applied in citrus orchard in China. The cooperative has established a demonstration base for citrus information management in the park and constructed a real-time monitoring and intelligent control system for the ecological information of citrus base, physiological development of tree fruits, and orchard video information, so as to master the main information of the orchard in a timely manner and to facilitate remote management and monitoring. Remarkable achievements have been made in the construction of the demonstration base, which has been well-received by the general public. Citrus growth environment data are collected through sensors, and the data are then forwarded, received, stored, and fused through wireless sensor nodes in IoT. In addition, the environmental parameters in the orchard are acquired in real time by means of the Internet, mobile APP platform, and SMS.

Accurate real-time monitoring revolutionized Wangbuliao citrus professional cooperatives. When the data exceeds the warning value, the system automatically alarms and undertakes reasonable control, such as automatic heating, irrigation, and so on. Figure 10.4 shows the IoT application case of citrus professional cooperatives in Yongquan Town, Linhai, Taizhou.

Zhejiang University and Ningbo City, Zhejiang Province, have jointly developed the digital precision cultivation technique of southern pear and the IoT system for the collection and processing of orchard environmental information. Through the establishment of a system database, the intelligent management information system, the disease and pest diagnosis expert system, and the wireless sensor network monitoring system of soil and environmental information for southern pear cultivation are developed to allow digital and precise cultivation management and intelligent information acquisition and monitoring in the growing process. The intelligent management of southern pear cultivation, the online diagnosis of southern pear diseases and pests in orchards, and the real-time monitoring and transmission of information are achieved, thanks to the interactive interface. As a result, the digital

Fig. 10.4 Application cases of Wangbuliao citrus professional cooperatives in Yongquan Town, Linhai, Taizhou, Zhejiang

Fig. 10.5 Intelligent management platform for digital precision cultivation of pear

management of southern pear precise cultivation and the collection and processing of environmental information in orchards are made possible. Figure 10.5 is an illustration of the digital management platform for precision cultivation of pears and the IoT system for the collection and processing of environment information orchards.

10.5 Summary

Fields and orchards are the main application scenarios of agricultural IoT. Compared with facility agriculture, the environment of field and orchard is more complex and accompanied with more uncontrollable factors. The application of the agricultural IoT in fields and orchards is based on the basic structure of IoT. Considering the special application scenarios of the fields and orchards, appropriate sensors and networking methods can be selected. At the application layer, through the use of diagnostic models or expert systems or real-time online diagnosis, the precision management of growth enabled by IoT is achieved.

IoT in fields and orchards, monitoring and controlling the growth of crops and fruit trees in an open environment, is subject to changes in the climate and environment. Which is why it is difficult to adopt IoT in fields and orchards. In open environments, the stability and durability of sensors, the stability of information transmission, and the reliability of decision making are all issues that demand further research.

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Chapter 11
Plant Factory IoT Management

Yong He, Pengcheng Nie, Bingquan Chu, and Dandan Kong

Abstract Plant factory, characterized by artificially controlled operation, is internationally recognized as the most advanced stage of developments in protected agriculture. Covering biological systems management, engineering management, and IoT management, plant factories can produce the planned crop products all year long, with short growth cycles and little pollution. Breakthroughs in artificial-lighting cultivation technology of plant factories have enabled crop production in non-arable lands such as skyscrapers, deserts, islands, ships, and polar regions. Therefore, the plant factory is considered a major countermeasure for the problems of this century, including population expansion, resource shortages, food security, and environmental pollution. Furthermore, it is also viewed as a way to achieve food self-sufficiency in future space engineering and space exploration. With IoT, thorough sensing and recognition, comprehensive interconnection, and deeper integration and analysis are possible, thus bringing intelligent control and decision of plant factories. In this chapter, main components and types of plant factories are illustrated, and applications of IoT systems in plant factories are outlined, so that readers may gain a comprehensive understanding of plant factory IoT.

Keywords Plant factory · IoT · Environmental control · Industrialized seedling production

11.1 Introduction

The global population is expected to reach approximately 9.7 billion by 2050 (United Nations 2019a), and 68 percent of the world's population is projected to be urban (United Nations 2019b). The problem of insufficient labor in agriculture driven by increasing urban population has become more and more prominent. Traditional crop farming, restricted by natural conditions (climate, land and water resources), features high labor intensity and low yield. Continued urbanization will

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bring new challenges to sustainability of food supply for cities. As living standards improve, the demand for fresh, clean, and safe agricultural products has increased. Research on urban agriculture, vertical farming, and plant factories has attempted to provide new perspectives for food production systems in cities (Gentry 2019; Graamans et al. 2017). Urban agriculture could ensure the supply of local fresh food. Considering the financial value of urban space, an economically viable enterprise in this regard would require extremely high productivity (Graamans et al. 2018; O'Sullivan et al. 2019).

Plant factory, as tech-intensive type of agriculture that features high yield, high efficiency, and high quality, is an advanced stage of the development of agriculture with controlled environment. Characterized by artificially controlled environment and factory operation, plant factory covers management of biological systems, engineering management, and IoT management (Yang and Zhang 2005a). Plant factory produces planned products all through the year with short crop growth cycles and little pollution. In such factories, the efficiency of land use and crop yield per unit area can be multiplied by stacking culture shelves vertically (Kozai and Niu 2016; Yang and Zhang 2005a). The extensive application of IoT technology marks a new round of development opportunities for plant factories and a symbol of smart agriculture in the twenty-first century. With IoT, thorough sensing and recognition, comprehensive interconnection, and deeper integration and analysis are possible, thus bringing intelligent control and decision of plant factories.

In this chapter, main components and types of plant factories are illustrated, and applications of IoT systems in plant factories are outlined, involving environmental control systems, CO_2 and nutrient solution supply systems, video monitoring and image transmission system, automatic logistics seedbed, intelligent robots, and computer remote automatic control system, so that readers may gain a comprehensive understanding of plant factory IoT.

11.2 Plant Factory Outline

11.2.1 The Concept of "Plant Factory"

The concept of "plant factory" was first proposed by Japanese scholars. Plant factory is a protected agriculture system that relies on computers to automatically and accurately control growing conditions, such as light, temperature, humidity, CO_2 concentration, and nutrient solution, thus enabling crop production all year long (Luna-Maldonado et al. 2016; Yang and Zhang 2005a). It mainly produces vegetables and fruits, flowers, herbs, and edible fungi. Plant factory is a tech-intensive mode of production that involves protected horticulture science, biotechnology, construction engineering, material science, information technology, and computer science (Yang and Zhang 2005b). It represents a new direction of agricultural development, and a focus in high-tech researches of global agriculture.

Compared to traditional agriculture production modes, the plant factory features the following advantages:

- More detailed production plan that can achieve annually balanced production
- Vertically stacked cultivation, which can significantly improve efficiencies of land and water use
- Higher crop yield per unit area
- Higher levels of mechanization and automation, lower labor intensity, and more comfortable working environment
- Safer and pollution-free products
- No or fewer influences from natural conditions like geography and climate
- Reduced transportation costs
- Advantages in producing rare, high-price, and nutritious plant products by combining with modern biotechnology

Plant factories could ramp up the efficiency of land use while keeping crops away from harsh climates; as a result, they have rapidly developed in Japan, the Netherlands, Denmark, Sweden, Norway, Austria, the United States, and Canada.

11.2.2 Main Components of a Comprehensive Plant Factory

In terms of space, a comprehensive plant factory is mainly composed of the following parts: seed laboratory, seeding room, seedling culture room, nutrient solution control room, cultivation room, air-conditioning room, central control room, cold storage, and delivery room. More specifically, the control system mainly includes airtight system, artificial lighting system, intelligent environmental control system, CO_2 supply system, circulation and sterilization system for nutrient solution supply, vertical cultivation system, video monitoring and image transmission system, computer control and remote controlling system, and intelligent transportation platform. Refer to Fig. 11.1 for a schematic diagram of a comprehensive plant factory.

11.2.3 Types of Plant Factory

11.2.3.1 Plant Factory with Artificial Lighting and Solar Lighting

Plant factory with artificial lighting and solar lighting is a factory mode that uses natural lighting in the daytime and artificial lighting at night or when it is clouded. This model, marked by low energy consumption, minimal climate impact, and stable crop production, is suitable for cultivating various flowering and fruiting plant species. However, this type of plant factory requires a large amount of electricity to cool down in summer, a season with sufficient sunlight and high temperature, and the stability of temperature is not as high as that of a totally enclosed plant factory

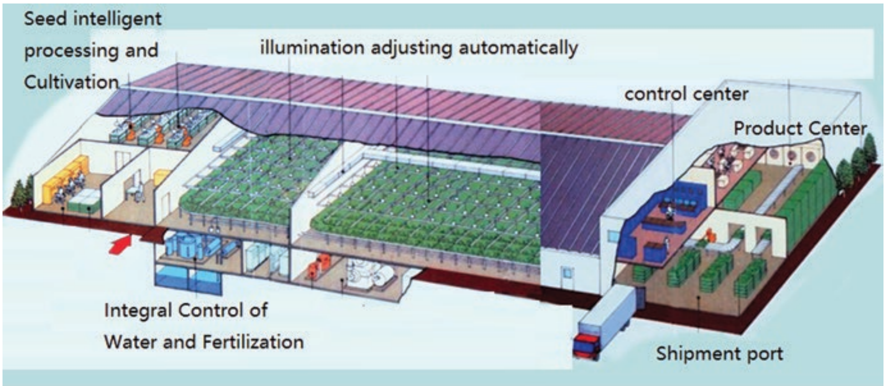

Fig. 11.1 Schematic diagram of a comprehensive plant factory. Note: The source of the diagram https://club.1688.com/threadview/46300110.htm

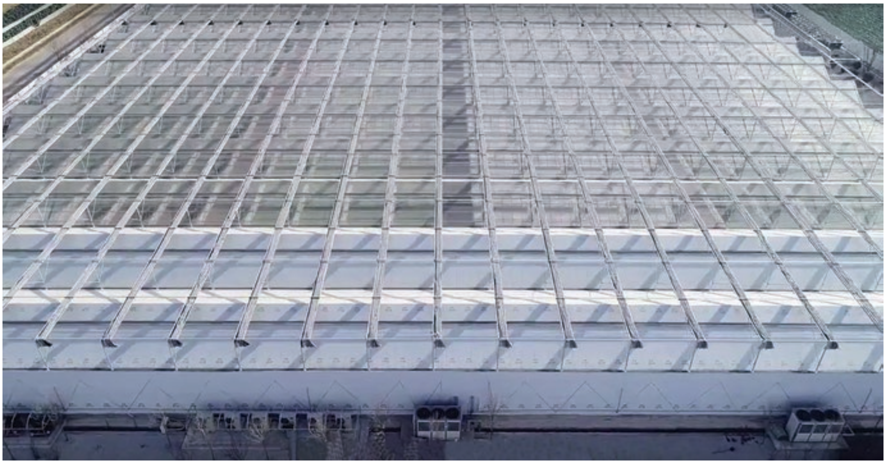

Fig. 11.2 A plant factory with artificial lighting and solar lighting. Note: The source of the photo https://v.qq.com/x/page/a0808pdr3uy.html?start=51

with artificial lighting. Currently, a large number of investors favor this type of plant factory (Fig. 11.2).

11.2.3.2 Plant Factory with Artificial Lighting

A plant factory that solely relies on artificial light sources (light-emitting diodes (LEDs), fluorescent lamps, high-intensity discharge lamps, and so on) features excellent air tightness and excellent insulation performance owing to its fully enclosed building structure. The indoor environment parameters and cultivation conditions (light, temperature, humidity, CO_2, nutrient solution) can be accurately

Fig. 11.3 Cultivation of a plant factory with artificial lighting

controlled, and the light-dark period can be adjusted accordingly (Yang and Zhang 2005b). Within such an environment, plants can grow steadily, and annually continuous production can be achieved. When compared with the plant factory that combines artificial lighting and solar lighting, this type of plant factory demonstrates a number of advantages, including higher planting density, higher energy efficiency, and higher utilization of water, CO_2, and land (Goto 2012; Graamans et al. 2018; Kozai 2013). Yet it also suffers from certain disadvantages, including higher early investment in facility construction and technical equipment and higher power consumption and operating costs (Graamans et al. 2018; Zhang et al. 2018). It is worth mentioning that the plant factory with artificial lighting is mainly used for cultivating seedlings, leafy vegetables, and mushrooms (Fig. 11.3).

11.2.3.3 Movable-Container Plant Factory

A movable-container plant factory is constructed using adiabatic plates for full isolation from the external environment. The variations in weather conditions have little effect on the climate of the cultivation space in a movable-container plant factory. The container plant factory is equipped with automatic environmental control system, lighting control system, and water circulation system to monitor environmental parameters, such as temperature, humidity, and CO_2 concentration inside

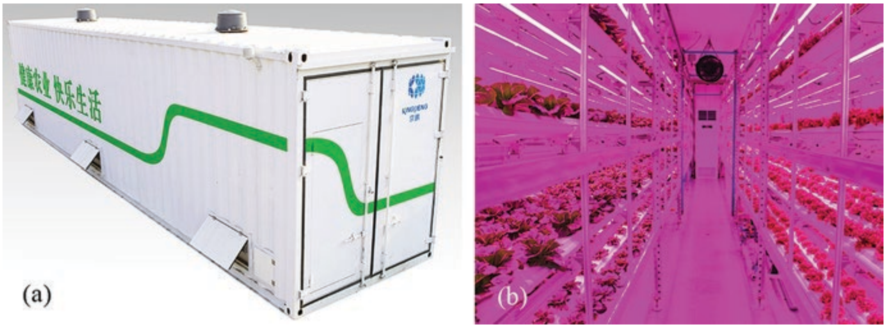

Fig. 11.4 A movable-container plant factory: (**a**) outside view, (**b**) inside view. Note: The source of the photo http://www.jingpeng.cn/page93?product_id=112

and outside the container. Furthermore, it allows automatic closed-loop control of environmental parameters, light parameters, and water pump. The factory is able to engage in all-weather artificial simulation and fully closed aseptic operation, making it suitable for cultivation research. The movable plant factory, as a high-strength container, adopts a modular design for easy lifting and transportation. It is capable of producing food anywhere, especially in ocean freighters, naval vessels, islands, border posts, and polar regions. Additionally, it also can be used as a base demonstrating and promoting plant factory technology (Fig. 11.4).

The plant factory constructed in the coldest polar regions ought to be well insulated; otherwise, it is difficult to build a stable cultivation space. In addition, solar or wind power generation systems are needed to provide the energy required for environmental control of the cultivation space. Currently, the University of Arizona in the United States has established this type of plant factory in the South Pole to supply fresh vegetables for staff working there.

11.2.3.4 Micro-Plant Factory for Households

The micro-plant factory is a fully closed and intelligent environment-controlled plant producing system that is suitable for households, allowing urban residents to experience the rural life by growing and picking vegetables at home. In such factories, vegetables are planted on multilayer hydroponic cultivation beds, where the nutrient solutions are provided on demand through an intelligent liquid supply system. The temperature, humidity, light, and wind speed in the system are adjusted by the intelligent environment-controlled system, while CO_2 is produced by humans. The intelligent monitoring system based on IoT makes it possible for the users to remotely monitor the micro-plant factory in real time via mobile phones and computers. The micro-plant factory comes with various cultivating forms and species. The size and the components of the cultivating box can be customized. One can create one's own special garden by planting leafy vegetables, mushrooms, flowers, or herbs. The micro-plant factory features multiple advantages, including small

Fig. 11.5 Micro-plant factory for households. Note: The source of the photo http://www.jingpeng.cn/page93?product_id=112

space occupation, ecological environment protection, extremely short distance between production and consumption, and considerable economic benefits. In the near future, the micro-plant factory will become an important model that urban residents could rely on to produce pollution-free vegetables. This type of plant factory also offers gorgeous views in four seasons, turning into safe and secure food on the table (Fig. 11.5).

11.2.3.5 Micro-Cabin Plant Factory

As a cultivation mode of producing plants in outer space using life support technology, the micro-cabin plant factory is an attempt by researchers in making plants grow normally in the weightless environment. This plant factory, designed to explore the practicability of plant cultivation on other planets, is still in an exploratory stage and has a wide development prospect, laying the foundation for human's next planet plan (Fig. 11.6). The United States has currently carried out cultivation experiments on the space station to solve the supply of fresh vegetables for astronauts.

Fig. 11.6 A micro-cabin plant factory designed for the space station. Note: The source of the photo https://mp.weixin.qq.com/s/D5-z3jsHujejUocARi5okA

11.2.4 IoT and Key Technologies of Plant Factories

11.2.4.1 IoT System Architecture of Plant Factories

The plant factory IoT system allows automatic operation, intelligent control, and standardized management of production relying on such IoT technologies as intelligent sensing, data transmission, automated control, scientific analysis, and decision. It consists of three layers, including the sensing layer, the transmission layer, and the application layer (Fig. 11.7). The functions of each layer are summarized below (Wang et al. 2018):

- The sensing layer mainly utilizes smart sensors, biochemical sensors, and cameras to sense environmental information of crop growth (temperature, humidity, nutrient solution, CO_2, and light) and physiological and ecological information of crops (growth properties, insects, and diseases).
- The transmission layer needs to build a three-level information transmission network of local control, factory monitoring, and intelligent agricultural IoT platform through wireless sensor networks, mobile communication networks, and wire communication networks, so that remote management and control of production can be achieved.
- The application layer mainly relies on environment simulation, intelligent control, intelligent decision, expert diagnosis, cloud computing, deep learning, big data, and other methods to be engaged in the sharing, exchange, and merging of information that is obtained from the sensing layer, thus achieving early-warning diagnosis, scientific decision, and intelligent management of various production processes of the plant factory.

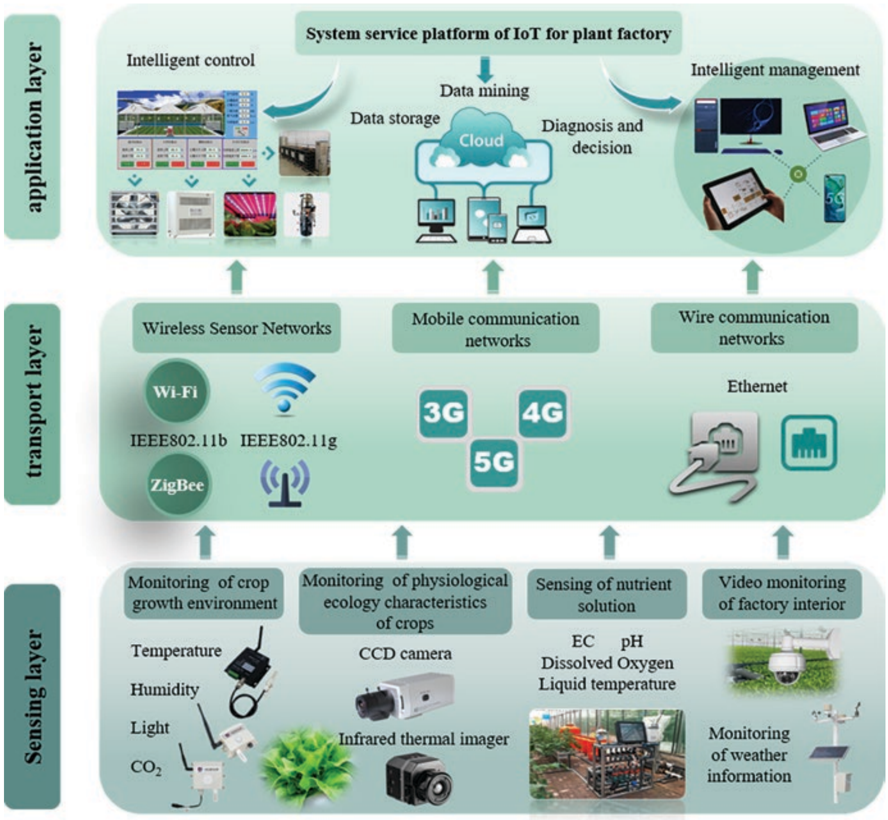

Fig. 11.7 IoT system architecture of plant factories

The aim of IoT system application is to offer comprehensive sensing of plant growth and environmental information and then to obtain the best growth conditions for crops through data processing, analysis, decision, and intelligent control. IoT systems can improve crop yield and quality and decrease costs like energy, water, fertilizer, and labor. As a consequence, high-yield, high-efficiency, high-quality, low-consumption, and safe and ecological production of plant factories can be achieved.

11.2.4.2 Key Technologies of Plant Factories

Sensing Technologies for Properties and Conditions of Plant Growth

Sensing technologies for properties and conditions of plant growth mainly adopt methods of smart sensors, machine vision, spectral analysis, and imaging to sense information of nutrient solution, greenhouse environment, and plant physiology and ecology.

Computer Simulation of Growth Environment

Thanks to computer simulation, the prediction and analysis of growth process and greenhouse environmental variations are achieved by mathematical modeling and computer simulation.

Information Transmission Technologies

Information transmission technologies, containing wireless sensor networks, mobile communication networks, and wire communication networks, aim to achieve remote supervision of crop production in plant factories and to ensure real-time stable information transmission. Additionally, it is required that a three-level (local control, factory monitoring, and intelligent agricultural IoT platform) network system of information transmission should be built.

Computer Intelligent Management

The methods adopted by computer intelligent management include deep learning, intelligent decision, cloud computing, and big data. Empowered by such adoptions, computer intelligent management achieves the analysis, diagnosis, and merging of the observed information involving data on plant, environment, cultivation management, production, and sales. It aims to offer rational decision-making and intelligent management of various production links of the plant factory.

11.3 Management of Plant Factories via IoT Systems

11.3.1 Supplementary Lighting Systems

As an energy source of plant required for life activities, light is also an important information medium that certain plants depend upon to complete the life cycle (Yang and Zhang 2005c). This makes the supplementary lighting system one of the most important environmental control systems in a plant factory. Factors such as light intensity, light quality (light spectral distribution or composition), photoperiod, and lighting mode significantly affect photosynthetic rate and plant growth (Harun et al. 2019; Wang et al. 2016; Zhang et al. 2015, 2018). Therefore, according to the light demand of different plants and various growth stages, it is essential that plant factories control light environment using IoT technology. The application of IoT technology can maximize photosynthetic efficiency while reducing energy consumption. Fluorescent lamps (FLS) are adopted extensively in plant factories with artificial lighting at an early stage due to their compact size (Shoji et al. 2013). High-pressure sodium lamps and high-pressure halogen lamps are also used in some plant factories as light sources. At present, most newly built plant factories use LEDs as supplementary light sources. LEDs are cold light sources that can be set close to the surface of leaves to supplement light, thus obtaining higher photosynthetic efficiency and making LED especially suitable for multilayer vertical cultivation systems.

The LED light source powered by a low-voltage power supply (from 6 to 24 V) is safer than that powered by high-voltage power supply. In addition, it saves nearly 80% of the energy consumed compared with an incandescent lamp with the same light efficiency. The changes in the LED current can achieve multicolor light emission of red, yellow, green, blue, and orange light. Studies have indicated that, instead of the full bands sunlight, plants only absorb light at specific wavelengths, such as red and blue light, for photosynthesis during the day, and that growth primarily takes place at night. A single-wavelength of LED can enhance photosynthesis in comparison with wide-band sunlight. Early artificial lighting contained large wavelengths of light other than red and blue, which led to high-power consumption. In particular, the infrared light was a thermal light source in early artificial lighting. Using LEDs at specific wavelengths to illuminate, the flowering and fruiting of plants can be adjusted, and their height and nutrition can also be controlled. As the chip technology further matures, the production of economical and practical LED light sources as well as the supporting control devices will be sure to play a major role in scaling up the adoption of plant factories (Fig. 11.8).

11.3.2 Intelligent Climate Control Systems

Plants could perform normal physiological activities and biochemical reactions only when under suitable temperatures. The temperature of environment and nutrient solution of the plant factory exerts significant effects on photosynthesis, respiration, transport of photosynthetic products, root growth, and the absorption of water and nutrients. Therefore, temperature control is essential for production within plant factories. In plant factories, temperature regulation is carried out by temperature sensors and automatic control systems. Temperature can be adjusted upward by a heating system, which generally consists of heat source, heating medium pipe, and radiator. The heat sources mainly include fossil fuels (coal, oil, and natural gas), electricity, waste heat, and geothermal resources, while the heating media include hot water, hot air, and steam (Yang and Zhang 2005c). Thermal-pump refrigeration systems and cold-water thermal storage systems are widely used for cooling in plant factories. Temperature control is currently one of the tasks that is accompanied with high operation costs in plant factories. To reduce costs, according to local conditions, wind power, solar power, and solar air conditioner can be used for heating and cooling. Moreover, geothermal resource and waste heat from power plants can be utilized for heating, making the system more economical (Togawa et al. 2014) (Fig. 11.9).

The relative air humidity is another critical environmental control parameter for plant factories. Humidity determines the water vapor pressure difference between the surface of leaf and the surrounding air; thus, humidity influences leaf surface evaporation. Low humidity results in large leaf surface evaporation, reduced inner

Fig. 11.8 Supplementary lighting system of LEDs

water and cell volume, low porosity, and fewer photosynthesis products. On the other hand, high humidity brings small leaf surface evaporation, excessive body water, and increase in stems and leaves, thus affecting the yield. Humidity also affects pests and diseases of plants. Under extremely high humidity (>90%), plants are susceptible to microbial attack, while under extremely low humidity, plants can be infected with powdery mildew and pests. Different plants have different requirements for the relative air humidity. Therefore, it is necessary to adjust the air humidity according to the type and growth stage of plants. In the automatic environmental control system, ventilation and heating are usually used for dehumidification, whereas spray and fan-pad cooling system are used for humidification.

11.3.3 Air Circulation Systems

When plants grow under moderate wind (3–4 m/min), the amount of CO_2 absorbed by the stomata increase significantly. Intelligent control of ventilation devices can effectively regulate the temperature, humidity, and CO_2 concentration in the cultivation room. Meanwhile, such control can make indoor gas distribution more uniform.

Fig. 11.9 Intelligent climate control systems

In particular, as CO_2 has a sinking property, convection ventilation can achieve uniform air supply on the surfaces of plant leaves. The air circulation system can significantly ramp up the seedling density to improve the utilization rate of space. In addition, it can also combine physical sterilization to achieve the sterilization of air in the cultivation space (Fig. 11.10).

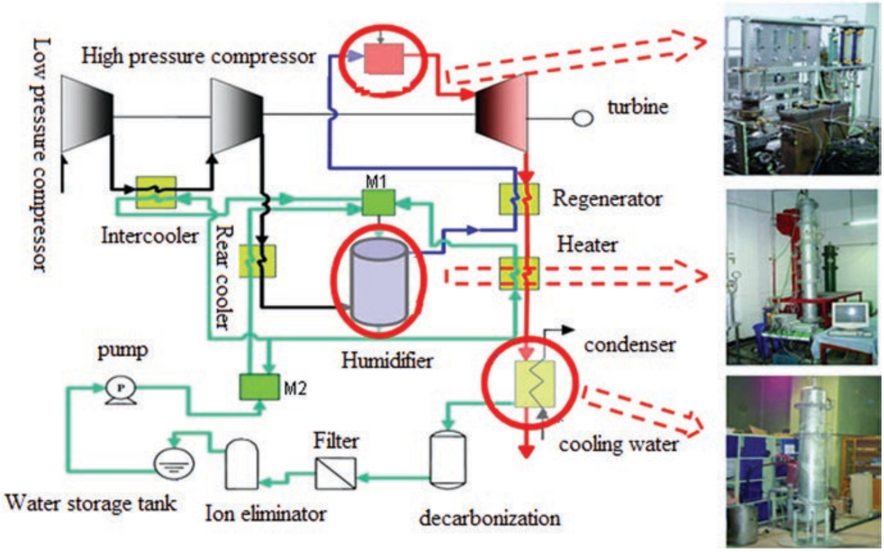

Fig. 11.10 Schematic diagram of an air circulation system

11.3.4 Nutrient Solution Circulation and Automatic Control System

The cultivation technologies of plant factories have evolved from solid substrate cultivation to hydroponics (NFT, DFT) and to aeroponic cultivation. Solid substrate cultivation is a culture mode that uses the solid substrate (gravel, rock wool, perlite, coconut bran, ceramsite, and so on) of water and fertilizer retention to support the root system of crops and provide certain moisture and nutrients for crop growth. The main supply method of nutrient solution is drip irrigation. Additionally, the nutrient solution supply system can be divided into closed-loop circulation system and open system. The difference between the two systems is that the former recycles the excess nutrient solution after absorbed by the substrate to the collection tank through the return pipe, while the latter discharges the excess nutrient solution out of the system through the drain pipe without recycling.

Hydroponics is a cultivation mode in which the roots of plants are immersed in the nutrient solution to obtain the water and fertilizer required for growth. There are, currently, three major cultivation techniques that are widely used, namely, deep flow technique (DFT), nutrient film technique (NFT), and floating capillary hydroponics (FCH). The nutrient solution layer of DFT is relatively deep. The plant is fixed by the planting tray, hanging over the solution surface, and the root system hangs down into the flowing nutrient solution. NFT allows the plant root system to spread flat on the bottom of the liquid tank, and the nutrient solution flows in a shallow layer from the upper end of the tank to the lower end. Aeroponic cultivation is a culture technique that uses a spray device to atomize nutrient solution into micron-level mist

Fig. 11.11 Nutrient solution circulation and automatic control systems

droplets and sprays them directly to the root system in an intermittent manner, so that the water and nutrients needed for plant growth can be provided. This technique addresses the contradiction of water and gas supply to the root system in hydroponics.

Charged with the task of delivering nutrient solution of appropriate formulation and concentration to each plant, the nutrient solution supply system is composed of a transportation system and a regulation-control system. The former consists of connected pipes, whereas the latter is composed of nutrient solution tanks, mother liquor storage tank, various detection probes, and a computer control system. Moreover, the nutrient solution supply system is also responsible for the regulation and control of EC value, pH, dissolved oxygen, and temperature of nutrient solution. The system offers solution that has sufficient dissolved oxygen, complete nutrient elements, and suitable pH and temperature to cultivated plants, so as to promote high-speed growth (Fig. 11.11).

11.3.5 CO_2 Supply Systems

CO_2 is an essential material for photosynthesis, which is why seemingly insignificant variations in CO_2 concentration can have major influence on the photosynthesis rate of plants (Kozai and Niu 2016). It can be inferred from this that CO_2 concentration is one of the major environmental factors in plant factories. CO_2 is quickly consumed in a limited cultivation space. If there is no external supply of CO_2, plants in the factory will grow poorly due to the lack of CO_2. The immense productivity of plant factories is inseparable from the compulsory supply of CO_2. The CO_2 supply system can maintain the CO_2 concentration required for photosynthesis of

Fig. 11.12 A CO_2 generator manufactured by ACME AGRO Group Limited

high-density plants in a plant factory, providing huge outputs of biomass. CO_2 supply devices currently used in greenhouses mainly include hydrocarbon-dependent CO_2 generators (burning hydrocarbons such as natural gas or kerosene to generate CO_2), carbonate-dependent CO_2 generators (using chemical reactions of carbonates and strong acids to generate CO_2), and CO_2 cylinders (Fig. 11.12).

11.3.6 Video Monitoring and Image Transmission Systems

The video monitoring and image transmission system, mainly composed of cameras, digital hard disks, computers, and control software, can carry out real-time online monitoring and video transmission. In order to achieve remote monitoring and diagnosis, cameras are generally installed in different areas of plant factories. These cameras are capable of 360° rotations and have variable focal lengths; thus, they can be counted on to observe the growth of plants from different angles. Installing this system allows easy remote diagnosis by experts. The experts can make clear observations of the stomata on surfaces of leaves and element deficiency diseases by a camera with an adjustable lens. The system can provide producers or researchers with a large amount of growth data for reference in making production decisions (Fig. 11.13).

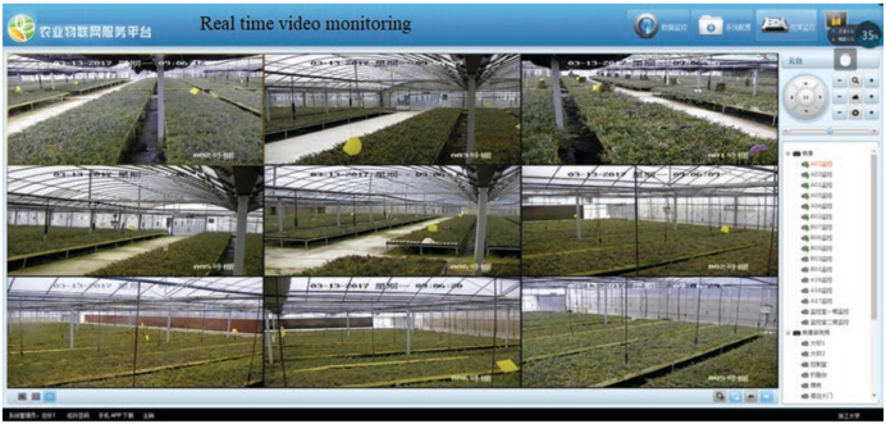

Fig. 11.13 Remote video monitoring platform

11.3.7 Automatic Logistics Seedbeds

Automatic logistics (movable) seedbeds are a major feature of an intelligent plant factory and an important part of the plant factory IoT system. Their emergence allows plant factories to achieve fully automatic production from sowing to harvesting, hence significantly saving investment on manpower. The logistics seedbed system is mainly composed of automatic movable platforms, single seedbeds, transverse guide rails, and longitudinal guide rails. The seedbed moves along longitudinal guide rails in the planting area driven by an automatic movable platform. When a new seedbed is pushed onto the rails, the previously placed seedbed will be pushed. Each set of transverse rails is equipped with two air-driven lifting rails. After the rails are raised, the seedbed can be moved along the lifting rails from the transverse rails to the planting area rails. The seedbed is lifted or dropped by the air cylinder and mechanical structure, so that the seedbed can switch the moving direction between the transverse guide rails and longitudinal guide rails (Fig. 11.14).

11.3.8 Intelligent Robots

As intelligent robot technologies mature, in future plant factories, most workers will be replaced by robots. A large number of production processes, such as grafting, transplanting, crop management, and harvest, will be done by robots. At present, relatively mature agricultural robots, including transplanting robots, grafting robots, cutting robots, logistics robots, routing inspection robots, and picking robots, that can be used in greenhouses and plant factories have been developed (Li et al. 2018; Zhang et al. 2019).

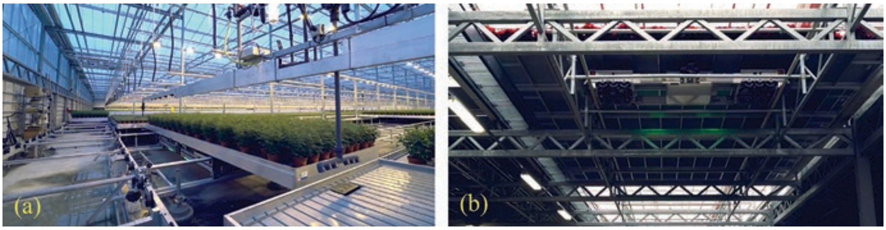

Fig. 11.14 Automatic logistics seedbeds: (**a**) side view, (**b**) bottom view

Japan and the Netherlands boast the most typical protected horticulture robot technology. At the end of the twentieth century, Japan developed a variety of production robots in the field of technology-intensive protected horticulture, ranging from grafting robots to cutting robots and harvesting robots. The Netherlands, as the global leader in greenhouse horticulture, rapidly developed robot technology based on the demand for precision management and precision control of greenhouses. For example, the cucumber picking robot developed by the Netherlands Institute of Agricultural and Environmental Engineering can reach the initial operating position within a short period of time, detect the accurate position and maturity of the cucumber through a vision system, and control the end effector to secure the cucumber and then separate it from the stalk (Hou and Xue 2019; Qi et al. 2019; Tu 2016; Wang 2015; Xu 2015).

11.3.8.1 Grafting Robots

As a kind of artificial vegetative propagation method, grafting technology is considered one of the most effective techniques to enhance the stress and disease resistance of fruits and vegetables and to achieve stable and high yield of crops. However, manual grafting suffers from such problems as high labor intensity, low efficiency, high cost, uneven levels, and low survival rate, which is why it fails to meet the needs of large-scale and standardized production of plant factories. Under this background, efficient grafting robots came into being.

The grafting robot is composed of a rootstock supply platform, a scion supply platform, a rootstock clamping and conveying manipulator, a scion clamping and conveying manipulator, a rotary cutting device, an automatic clamp feeding mechanism, a seedling conveying belt, a machine control system, and an air source. The working process of grafting robot can be described as follows (Chu et al. 2017):

- Seedling supply. The operator takes out the rootstock seedling and scion seedling from the trays on the left and right sides and places them on the corresponding supply stands. The two supply stands then rotate to send the rootstock and scion to the corresponding conveying manipulators.
- Seedling clamping and conveying. The manipulators for rootstock and scion conveying extend simultaneously and clamp the rootstock and scion from the supply

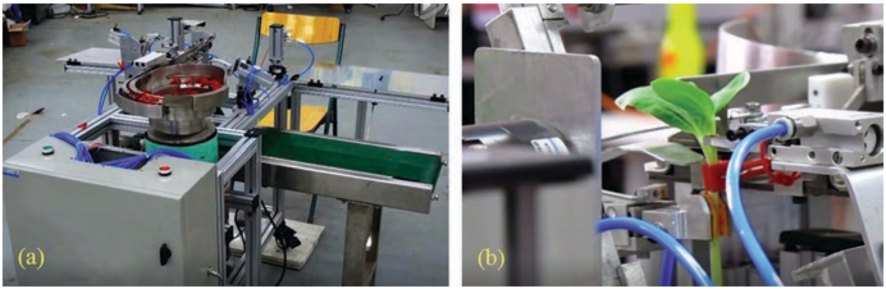

Fig. 11.15 A grafting robot: (**a**) appearance, (**b**) partial enlarged detail of grafting (developed by China Agricultural University, Key Laboratory of Ministry of Agriculture for Soil-Machine-Plant System Technology). Note: The source of the photo http://www.360doc.com/content/16/0604/22/30214551_565099707.shtml

stands. Then, after retracting, they rotate to send the rootstock and scion to the cutting position.

- Cutting seedlings. The rotary cutting mechanism drives the blade to rotate, cutting off the stalk of the scion and a cotyledon of the rootstock together with the growing point, thus forming a beveled cut.
- Combining and fixing. The rootstock manipulator and scion manipulator extend toward each other and bind the cutting surfaces of the two seedlings together. Then the automatic clamp feeding mechanism transports the grafting clamp to complete fixing.
- Seedling conveyance. The clamping claws of the rootstock and scion manipulators are opened, and then the grafted seedling falls onto the conveyor belt along the chute and is conveyed out of the machine.

The emergence of grafting robots has replaced the traditional manual grafting method that rely on bamboo sticks or blades, freeing people from monotonous seedling culture operations. The grafting robot is fast and efficient and saves labor costs. It is not only a high-quality and efficient modern agricultural production technology but also an integral part of the plant factory that cultivates melons (Fig. 11.15).

11.3.8.2 Transplanting Robots

The transplanting of plug seedlings refers to the process of transplanting seedlings from a high-density plug tray to a low-density one or a growing pot. It is a simple, time-consuming, labor-intensive, and repetitive operation, whereas manual transplantation is slow and inefficient. However, the transplanting speed could be faster by 4–5 times with improved stability using an automated transplanting robot.

The transplanting robot for plug seedlings is mainly composed of a mechanical arm, an end effector, a machine vision system, a computer control system, and a seedling tray conveying device. The main workflow is described below (Ren 2007):

- The seedling tray to be transplanted is located on the conveying mechanism, the seedlings suitable for transplanting is determined by the machine vision system, and the center position information of the seedling hole is obtained.
- The computer communicates with the PLC through a serial communication controller and transmits the position information acquired by the vision system to the PLC.
- The seedling tray continues to move to the grabbing area, and the position sensor signal is detected by the PLC.
- PLC controls the stepper motor to drive the mechanical arm to move above the seedling tray, and at the same time, it also controls the solenoid valve to push the cylinder. The seedlings are grabbed by the end effector at last.
- In the same way, the PLC controls the mechanical arm to move to the low-density plug tray and release the seedlings, completing a transplanting action at the end.

The high-speed automatic transplanting robot for plug seedlings are essential to reducing labor costs and improving the production capacity of plant factories (Fig. 11.16).

11.3.8.3 Intelligent Logistics Robots

Automatic Seedbed Transport Platforms

In a plant factory with vertical cultivation mode, an automatic seedbed transport platform can be relied on to transport the planted seedbed from the seedling culture workplace to the appointed cultivation shelf and then push it into the specific layer according to the computer instruction. During the harvest stage, the vehicle can move the seedbed from cultivation workshop to the harvesting workshop. Adopting the intelligent transportation platform, labor costs can be significantly cut, and the efficiency of bed transportation can be improved (Fig. 11.17).

Intelligent Transport Vehicles

The major components of an intelligent transport vehicle include a wheeled chassis, a layered loading frame, a visual navigation system, and an embedded control system. The four-wheel independent driving capacity gives the vehicle sound climbing

Fig. 11.16 Transplanting robot for plug seedlings: (**a**) grabbing seedlings, (**b**) planting seedlings. Note: The source of the photo https://v.qq.com/x/page/x0354mxfa9o.html

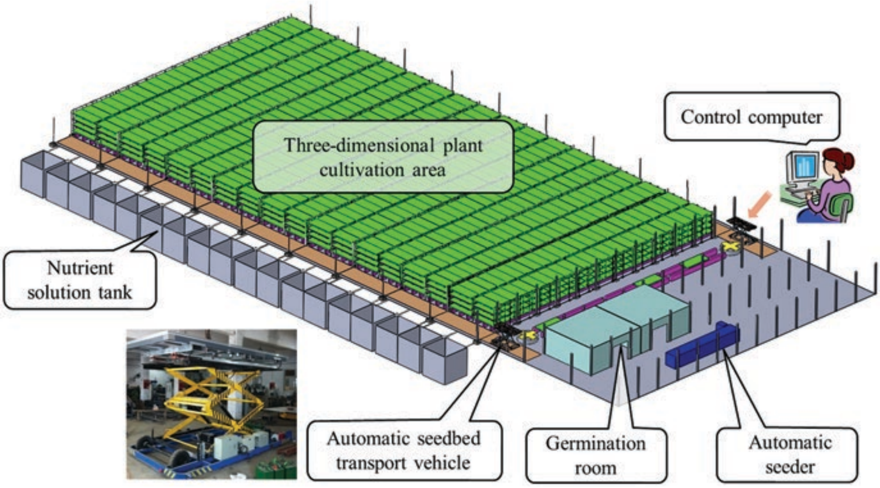

Fig. 11.17 Automatic seedbed transport systems. Note: The source of the photo https://wenku.baidu.com/view/5996321014791711cc79178f.html

and over-obstacle capabilities, as well as flexible steering performance. In addition, multi-sensor fusion of vision camera and ultrasonic sensor allows the vehicle to achieve autonomous navigation and obstacle avoidance. The intelligent transport vehicle generally comes with multiple operation modes, including manual software operation, remote control operation, and autonomous visual navigation operation (Fig. 11.18).

11.3.8.4 Intelligent Inspection Robots

During the growth of crops in plant factories, regular inspections are conducted to monitor the growth state of crops and the conditions of pests and diseases, to collect information on growth, to timely remove weak seedlings, to carry out pest and disease control, and to regulate the growth environment. The huge workload of management staff makes it difficult to reduce the labor cost of plant factory operations. Applying intelligent inspection robots, the growth state of crops is monitored in real-time via machine vision technology, and information on the growth environment is collected. All these data are then transmitted to the IoT cloud platform, which proceeds with environmental regulation and control of plant diseases and pests based on the information. The research and development of intelligent inspection robots will contribute to the creation of intelligent control and big data management of plant factories and reduce labor input. Moreover, intelligent inspection robots are critical for promoting the commercialization of plant factories.

An intelligent inspection robot is primarily composed of a computer control system, a movable platform, navigation and positioning system, high-definition camera group, environmental monitoring sensors, and image data transmission systems.

Fig. 11.18 An intelligent transport vehicle developed by Suzhou Agribot Automation Technology Co., Ltd

When working in a greenhouse or a plant factory, the inspection robot autonomously moves along the crop cultivation lines and collects environmental parameters such as temperature, humidity, CO_2 concentration, photosynthetic radiation, and wind speed, together with three-dimensional fixed-point images of crops through multiple sets of cameras. The images are analyzed by the analysis software; consequently, the plant height, fruit color, and pest and disease status are intelligently identified. The fruit ripeness can be determined by comparing the objective color values with the standard color values. In addition, the fruit-bearing conditions can be used to predict yield, thereby assisting production management (Fig. 11.19).

11.3.8.5 Fruit and Vegetable Picking Robots

Picking is one of the most time-consuming and labor-intensive links in the production processes of fruits and vegetables. The labor costs required in this part accounts for about 40–50% of that required by the entire cultivation process. Due to the large-scale, structured, and standardized cultivation, plant factories are especially suited for the adoption of robotic picking, which significantly reduces labor and production costs. Thanks to the developments of vision sensor technology, multi-sensor

Fig. 11.19 An intelligent inspection robot. Note: The source of the photo http://www.taihainet.com/news/fujian/gcdt/2019-06-18/2274873.html

fusion technology, and AI technology, currently, picking robots applied for fruits and vegetables, such as tomatoes, cucumbers, bell peppers, and strawberries, have come into being.

The major components of the picking robot for fruit and vegetable include a computer control system, cameras, a picture processor, a manipulator, a mechanical arm, an end effector, and a walking mechanism. While working in a plant factory, the robot can obtain accurate information relating to the size, color, and shape of the fruit through cameras. Additionally, it can determine the maturity of fruits and create three-dimensional spatial information of the object to be harvested. More specifically, relevant signals are transmitted to the manipulator to guide the mechanical arm and the end effector to complete the tasks of grasping, cutting, and recycling. The intelligent picking robot can achieve autonomous navigation, automatic identification, and unattended picking operation. Its success rate of picking can reach more than 90%, which means that it can solve the complex problems of fruit and vegetable harvesting. Some picking robots are even equipped with lighting device and thus can work during both daytime and night. Currently, picking robots are still in the experimental stage and have not been put into practical application on a large scale. As signature products of smart agriculture, they are expected to be commercialized and extensively adopted in plant factories in 5 years (Fig. 11.20).

Fig. 11.20 A picking robot based on binocular stereo vision (developed by China Agricultural University, Key Laboratory of Modern Precision Agriculture System Integration Research, Ministry of Education)

11.3.9 Computer Remote Automatic Control System

The computer remote automatic control system is commonly known as the brain of a plant factory, and each of the aforementioned systems works to serve this system. Relying on the system, one is able to monitor and control all environmental factors and cultivation factors with plant factories. For example, when the temperature sensor detects a value that exceeds the maximum limit, the computer will issue a command to turn on the cooling system for reducing the temperature, and when the temperature drops below the minimum limit, the computer will send an instruction of turning on the heating system to increase the temperature. The same applies to the control of other environmental/cultivation factors, such as humidity, light, and nutrient solution. The relative stabilities of those factors are achieved through closed-loop feedback control of the system. After installed, the automatic control systems can also be connected to a computer to implement remote control using software. The technicians can complete all operation parameters settings, expert mode switching, and image processing in the office.

11.4 Research Progress on IoT Technologies in Plant Factories

In recent years, IoT technologies have been extensively adopted in greenhouses and plant factories for environmental regulation, monitoring of plant physiology and ecology, intelligent management of cloud platform, and rational decision-making. Researchers have carried out a large number of application studies of greenhouse IoT system on the acquisition and transmission technologies of information relating to growing environment, simulation of the growth process, and environmental control (Li and Wang 2014). In addition, machine vision, artificial intelligence, cloud computing, big data, and other information technologies have also been introduced into IoT systems of greenhouses and plant factories (Tzounis et al. 2017; Wang et al. 2018).

In terms of sensing and transmission of greenhouse environmental information, the environmental control system with wireless sensor networks has become the prime choice of greenhouse IoT systems (Ojha et al. 2015; Rodríguez et al. 2017; Talavera et al. 2017). Concerning environmental intelligent regulation, Harun et al. (2019) proposed a new approach of using IoT technology as a remote monitoring system to control indoor climate conditions. In order to collect real-time data of the plant experiment and monitor the environmental parameters, an intelligent embedded system was developed to achieve automatic control of LED parameters, including spectrums, intensity, and photoperiod. To stabilize the production environment of salad-cultivating plant factories, Deng et al. (2018) developed a highly valid kinetic model using system dynamics and experimental data, and the pattern of optimal closed-loop control of temperature, aerating rate, and light intensity were determined based on the gradient of stored-energy function of the salad-cultivating plant factory (derived from Hamilton-Jacobi-Isaacs equation). Digital and real-time simulation results demonstrated that the closed-loop control system could overcome internal changes and external disturbances to stabilize the plant factory at an operating point and maintain sound salad yield.

In order to effectively monitor the growth of crops, machine vision technology based on the capturing and processing of image and video is utilized in plant factories and greenhouses. Chen et al. (2016) designed an automated weight measurement system, comprising a weight measurement device and an imaging system, for hydroponic plants of a plant factory. The system continuously measures the plant weight throughout the entire growth period without impacting growth. Moriyuki and Fukuda (2016) developed a high-throughput diagnosis system based on the measurement of chlorophyll fluorescence for a commercial plant factory. The diagnosis system depends on a high-sensitivity CCD camera and an automatic transferring machine to capture chlorophyll fluorescence images of seedlings. Machine learning is then utilized to accurately predict plant growth based on leaf size, amount of CF, and circadian rhythms. This system can be used as advanced seedling diagnosis technology to identify and cull low-grade plants at an early stage, which is why it plays a major role in avoiding major losses. Based on machine vision, Franchetti et al. (2019) proposed a novel method, combining 3D reconstruction, leaf segmentation, geometric surface modeling, and deep network estimation, for the accurate prediction of the phenotype features of plants, including height, weight, and the size of leaves. A greenhouse monitoring system for disease recognition of leaf vegetables was constructed by Ma et al. (2015a, 2015b, 2017) using the environmental information observed by sensors and the video information monitored by cameras. Liao et al. (2017) created an IoT system that can simultaneously monitor environmental factors of the greenhouse and the growth status of *Phalaenopsis*. Liao also proposed an image processing algorithm based on the Canny edge detection method, the seeded region growing method, and the mathematical morphology to estimate the leaf area of *Phalaenopsis*. Monitoring the growth of *Phalaenopsis* may be conducive to obtaining optimal cultivation conditions.

Cloud service technology is particularly important to the real-time, remote monitoring of environment and crops. On-site sensors obtain various types of information and transmit them to the cloud platform that performs data management and uses artificial intelligence, data mining, simulation models, expert knowledge, and other technologies for decision services to achieve intelligent management and control of greenhouses (Wang et al. 2018). Cui et al. (2015) built a cloud-computing greenhouse IoT service platform that provides intelligent environmental monitoring, cloud storage, and analysis of large-scale data, real-time cloud early warning, and personalized cloud services. Çaylı et al. (2018) developed a cloud-based, low-cost environmental monitoring system in greenhouses via open-source hardware to monitor climate data of agricultural practices for small businesses and rural areas.

Spectrum analysis and imaging technologies have evolved into major technical detection methods in agricultural research, production monitoring, and plant phenotypes, such as estimating leaf water content (Yi et al. 2013), assessing crop health (Liu et al. 2010), detecting pests and diseases (Mei et al. 2014; Weng et al. 2018), and identifying seed quality (Sun et al. 2019). As spectrum analysis technologies, picture processing technologies, and spectrum online detection technologies progress, in the future, spectrum analysis and imaging technologies will become the key monitoring technologies to improving the IoT systems of plant factories.

11.5 Summary

Currently, the plant factories have been recognized as the most advanced stage of protected agriculture development all around the world. Breakthroughs in artificial-lighting cultivation technology and IoT technology of plant factories have made crop production in non-arable lands, including skyscrapers, deserts, Gobi, islands, ships, and polar regions, come true. Therefore, plant factory is considered a critical way to solve the problems of the twenty-first century, ranging from population expansion and resource shortages to food security and environmental pollution. It is also viewed as an important means to achieve food self-sufficiency in future space engineering and space exploration.

Nevertheless, plant factories still face problems like high initial investment in equipment, high operating costs, weak market competitiveness, and insufficient profit. As such, progress on the industrialization of plant factory has been slow. In recent years, interested institutes and enterprises have focused on improving the automation and intelligent operation of plant factories and reducing running costs through the construction of intelligent environmental control systems and IoT system. In particular, they attach importance to the research of LED light sources, the development of efficient nutrient solutions and intelligent robots, the utilization of clean energy (solar energy, geothermal energy, waste heat, etc.), and the application of big data analysis and scientific decision. The commercial prospects of plant factories will be increasingly exciting, as intelligent environmental control systems improve, energy and labor costs decrease, and the market positioning of products become clearer.

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Chapter 12
Livestock and Aquaculture IoT Systems

Pengcheng Nie, Yong He, Fei Liu, Chunxiao Mi, and Chengyong Cai

Abstract Recent years saw the introduction of IoT in livestock farming and aquaculture. Concerning livestock agriculture, real-time information on breeding environment can be acquired through intelligent sensing, quick and safe transmission, and intelligent processing. Furthermore, with the help of computers, real-time monitoring of the breeding environment, fine feeding, monitoring of animal conditions, disease diagnosis and early warning, and breeding management have become available. In terms of aquaculture, water environments can be regulated and maintained in a proper state using IoT. Combined with machine vision technology, information on food intake of aquatic products can be acquired, which can be used as the basis to determine the levels of hunger and to achieve accurate and intelligent feeding. This chapter offers an elucidation on both of the abovementioned breeding, i.e., livestock farming and aquaculture.

Keywords Livestock IoT system · Aquaculture IoT system · Environmental monitoring · Intelligent multifunction

12.1 Introduction

Livestock farming and aquaculture heavily contribute to China's gross domestic product. Against such a backdrop, the application of IoT in these field, increasingly popular these days, could translate into significant improvements in both yield and quality. A demonstration of these benefits will be laid from the following aspects.

China, a global power in agriculture, ranks number one globally with respect to the production volume of livestock farming. As living standards rise, the consumption of livestock and poultry products grew rapidly. The industry of livestock farming, supported by such growth in demand, expanded constantly, attracting a large number of rural surplus labor and improving farmers' income. As a result, livestock

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farming now occupies an increasingly larger proportion of all agricultural revenue. The basic characteristic of modern livestock farming, an intensive industry with large investment, high yield, and remarkable benefits, is that the industry is capital-intensive and labor-intensified, the latter of which is evident when compared with developed countries. At present, as the economy grows further, the labor-intensive agriculture has begun to transition to capital-intensive agriculture. However, both types of intensive productions consume a great deal of labor and resources, and both have a negative impact on the environment to some extent. By adopting IoT, resources can be used rationally, environmental pollution can be relieved, and a high-quality and efficient mode of livestock farming can be established. The following is a summary of the application of the IoT in each link of livestock farming.

Intelligent monitoring of breeding environment. Real-time information of the farm, such as temperature, humidity, light intensity, air pressure, dust density, and concentration of harmful gases, is collected through smart sensors, and the information is then transmitted via either wireless or wired means to a remote server. At last, based on the decisions made by the server-side model, related control equipment are driven to make the appropriate adjustment, thereby achieving the intelligent management of livestock farming environment. Doing so reduces the frequency entering and exiting the workshop, avoids the spread of diseases, improves epidemic prevention, ensures safe production, and maximizes production benefits.

Precision feeding. Studies on livestock nutrition and research on rational feeding hold great significance to the development of livestock farming, resource efficiency, cost reduction, the alleviation of pollution and disease occurrence, and production safety. Precision feeding is achieved by establishing the quantitative relationship model among the growth stage, feeding rate, and feeding amount of different livestock according to the nutritional requirements in each breeding stage and the experience of breeding experts. Moreover, using IoT technology, the environment and group information related to precision feeding can be acquired, and the decision-making system of precision feeding can be built.

Thorough monitoring of livestock reproduction. In livestock farming, by using information technology to improve reproduction efficiency, the number of livestock raised for reproduction can be reduced, thus lessening the production costs and the costs of fodder and forage resources. Therefore, it is essential to provide the most suitable environment for livestock reproduction and to comprehensively manage and monitor livestock reproduction with sensors, RFID, and other sensing technologies to record the estrus of male and female livestock as well as the mating and breeding environment.

Digital management of production. As the industry expands increasingly, recording the day-to-day livestock information using the traditional paper cards can no longer meet the actual needs of production. Relying on IoT technologies, such as the two-dimensional code and radio frequency technology, we can make possible the efficient recording, query, and summary of production information, including growth, reproduction, epidemic prevention, disease, diagnosis, and treatment, based on mobile terminals, providing the critical support for decision-making in high-efficient production.

Aquatic products, a major source of nutrients for humans, contain high-quality protein, low-fat content, rich minerals, and vitamins. More than 15% of the protein intake from animals comes from aquatic products. In 2016, China's consumption of aquatic products reached 69.01 million tons, exceeding pork consumption. It is expected that China's aquatic product consumption will reach 70 million tons by 2023. It can be seen that aquatic products have become an essential part of life. In recent decades, the excessive consumption of marine resources and the destruction of the marine environment have caused severe damages to the marine ecological balance. In response to the problems and challenges, many countries have adopted a series of measures. For instance, China has issued a number of policies and regulations to introduce structural reforms to aquaculture, to rationally plan offshore fishing, and to reduce offshore aquaculture. Since reform and opening up, the Chinese government has pointed out that the development of aquaculture should be focused on cultivation and that vigorous efforts should be made to develop aquaculture so as to reduce the proportion of capturing. Moreover, the government also made clear that innovative approaches for an open marine aquaculture system in the new era should be explored. In 2018, China's total aquaculture production reached 50 million tons, accounting for 78% of all aquatic products sold. Currently, about 45% of the world's aquatic products come from aquaculture. In 2018, the production volume of global aquatic products increased by 2.1%, reaching 178.8 million tons, and though China's aquaculture production accounted for the largest proportion in the world, the country still suffers from many problems in aquaculture. At present, the high production of aquatic products in China is primarily a result of the large-scale consumption of waters and land. This wasteful development model runs counter to green and sustainable development. In addition, the vast majority of farmers still practice the traditional extensive aquaculture model. People involved in aquaculture depend on personal experience to determine the suitability of the farming environment, and their methods tend to be highly subjective, such as observing color and smelling (Guan et al. 2008). Additionally, there are also methods that include laboratory testing, which are time-consuming and labor-intensive. Feeding also relies on experience, a reliance that often results in inaccuracies. Excessive feeding will leave uneaten baits in the water, leading to problems such as water quality degradation, environmental pollution, and aquatic diseases, whereas insufficient feeding will reduce the quality of aquatic products. At the same time, as living standards improve, the demand for high-quality aquatic products has gradually risen, calling us to improve aquaculture technology and achieve efficient aquaculture (Chen 2018).

The *Thirteenth Five-Year Plan for National Aquaculture Development* prioritized innovation and adhered to the innovation-driven strategy. The plan advocated the application of modern technology and equipment and promoted the implementation of smart aquaculture (Huang et al. 2015). The *Thirteenth Five-Year Plan for Information-Based Agriculture* aimed at the integration of information technology and agriculture, including the application of IoT, big data, intelligent equipment, and other technologies to aquaculture (Lee 2000). Therefore, it is of major practical significance to apply IoT, "Internet +," artificial intelligence, and other technologies to modern aquaculture. Information-based and intelligent aquaculture has emerged as an essential way to solve existing problems in aquaculture. Eco-friendly aquaculture is a concept that focuses not only on the economic benefits of the aquaculture but also on the environment. In eco-friendly aquaculture, all aspects of aquaculture and production are strictly controlled, wastes are reused, and a development model of sustainable aquaculture is formed. Adopting modern technologies, such as intelligent equipment, IoT, “Internet +,” artificial intelligence technology, and efficient ecological aquaculture, intelligent aquaculture can be achieved, which effectively reduces labor costs and meets the development requirements and trends of modern aquaculture. In this respect, intelligent equipment are applied to high-efficiency eco-friendly aquaculture. Real-time monitoring of water quality is possible with IoT technology, and automatic control is undertaken based on water quality information. Relying on artificial intelligence technology, accurate feeding of bait, and intelligent warning of aquatic diseases are achieved. At last, intelligent, information-based, and eco-friendly aquaculture will come into being.

12.2 Application of Livestock Agriculture IoT System

12.2.1 Architecture of Livestock Agriculture IoT

Similar to the general structure of IoT, the IoT system for livestock farming also consists of three layers: perception layer, network transmission layer, and application layer. Such a structure enables real-time online monitoring and control of the farming environment through the integration of the intelligent sensing technology and equipment for livestock information, wireless transmission technology and equipment, and intelligent processing technology. Refer to Fig. 12.1 for the overall framework of the IoT system for livestock farming.

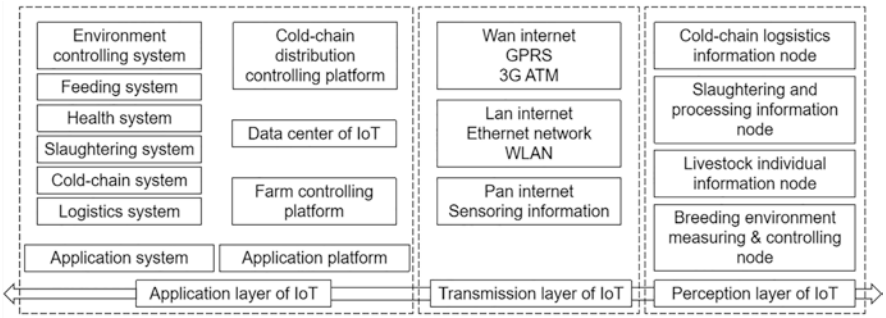

Fig. 12.1 The general framework of IoT system for livestock farming

12.2.1.1 Perception Layer of IoT

The perception layer, the "eyes" of the IoT system for livestock farming, detects, identifies, locates, tracks, and monitors the farming environment primarily using technologies that include sensor technology, radio frequency identification (RFID) technology, two-dimensional code technology, video and image technology, and so on. Sensors are used to collect environmental parameters, such as temperature, humidity, light, carbon dioxide, ammonia, and hydrogen sulfide; RFID and two-dimensional code technology are used to automatically identify individual livestock; and video and image technology is used to capture multiple types of environmental information (Niu et al. 2013).

12.2.1.2 Transmission Layer of IoT

The transmission layer transfers information from the perception layer to the application layer. Its wireless sensor network covers wireless acquisition node, wireless routing node, wireless sink node, and network management system. Wireless RFID is adopted for information collection and transmission in the local area of the site. It is worth mentioning that long-distance data transmission employs GPRS communication technology and 3G communication technology.

12.2.1.3 Application Layer of IoT

The application layer is divided into the public processing platform and the specific application service system. Various kinds of middleware and common core processing technologies are included in the public processing platform, through which in-depth integration of information technology and livestock farming is achieved, and the sharing, interconnection, decision-making, summary, statistics, and so on of the product information are enabled. For instance, the core functions of intelligent livestock farming that involve intelligent control, intelligent decision-making, diagnostic reasoning, early warning, and prediction are made possible with the support of the application layer. The specific application service system, the highest level of IoT-enabled production model, mainly comprises various specific agricultural production process systems, such as livestock farming system, product logistics system, and so on. The specific application of these systems could ensure the correct planning prior to farming, so as to improve the utilization of resources, allow fine management of production, enable efficient circulation after production, and achieve safety traceability. In such a manner, high yield, high quality, high efficiency, eco-friendliness, and safety of the industry could be promoted.

On the basis of the above framework, the environmental control system of IoT-enabled livestock farming is built and developed, and specific application tests are conducted in the process of livestock farming in accordance with the actual requirement.

12.2.2 Main Management and Applications System for Livestock Agriculture

12.2.2.1 Environment Monitoring System for Livestock and Poultry

To design and develop the environmental control system for livestock farming, the interrelationship among various environmental factors in the system needs to be ascertained: when a given factor changes, the system automatically changes and adjusts the environmental factors to create the fitting environment for growth and reproduction.

In view of the lack of technology and means for effective information monitoring and the insufficiencies in online monitoring and the control of farming environment in China's existing livestock farms, the livestock environment monitoring system has adopted IoT technology to realize real-time online monitoring and control of farming information (Wu 2014).

In the specific process of designing and developing the livestock environment control system, the system is divided into four parts: intelligent sensing subsystem, automatic transmission subsystem, automatic control subsystem, and intelligent monitoring management platform.

Intelligent Sensing Subsystem
Intelligent sensing subsystem, located at the bottom of the IoT system, is mainly applied to perceive the quality of the farming environment. For instance, the subsystem detects the level of ventilation in barns, temperature and humidity, dust concentration, light, carbon dioxide, whether heating or cooling is needed, and whether hydrogen sulfide and ammonia are in the best state. Collecting such information and transforming them into electrical signals through the corresponding and special sensors is the primary way to achieve automatic detection and control, which facilitate the transmission, storage, and processing of information. The schematic diagram of the information collection structure of livestock environment is illustrated in Fig. 12.2.

Automatic Transmission Subsystem
The automatic transmission subsystem uploads the collected information through wired and wireless means, i.e., it transmits the control information above to the receiving device below.

Image information transmission, urgently needed in livestock production, provides technical support for early warning of diseases and insect pests, remote diagnosis, and remote management. To effectively guarantee the quality and performance of the transmission of image, video, and other information, cable network is constructed in livestock farms to support the transmission of video surveillance. The video data are then sent to the monitoring center, allowing remote observation of real-time video inside the farms and enabling image capture and snapshot, triggering alarms, timed video, and so on for the designated area of the farms.

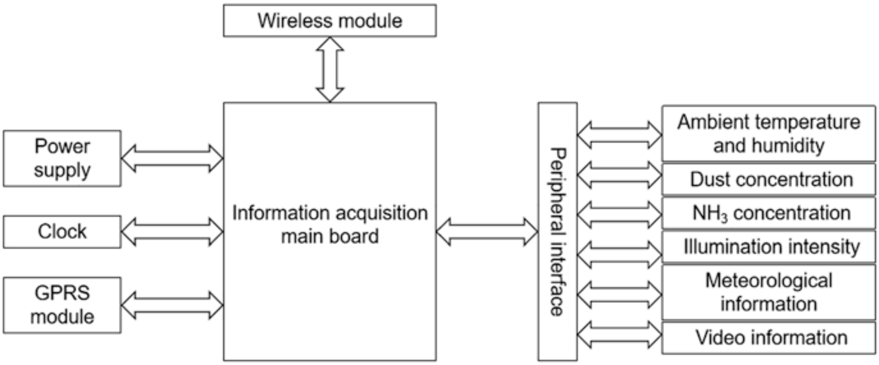

Fig. 12.2 The schematic diagram of the information collection structure for livestock environment

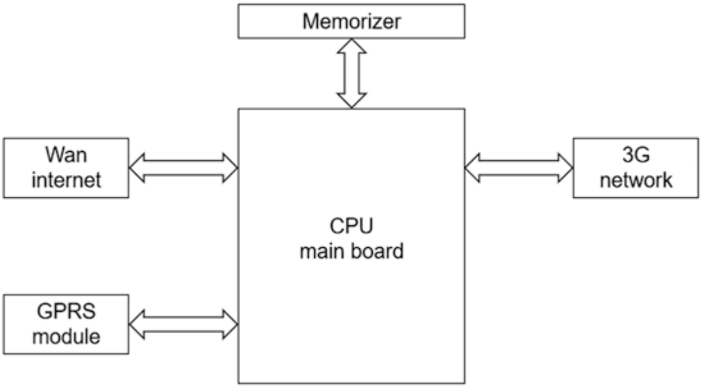

Fig. 12.3 The schematic diagram of transmission node structure

The transmission layer makes it possible to reliably transmit the collected information. In order to enhance the reliability of information transmission, the multipath information transmission mode is adopted. The chain structure unit of the transmission layer is the transmission node, the basic form of information transmission is the point-to-point transmission, and the multi-hop remote transmission of information is realized via the multi-node configuration platform. The structure of the transmission node is designed according to the basic functions of the transmission node (as shown in Fig. 12.3).

Automatic Control Subsystem

Through intelligent algorithm and expert system, the control layer achieves the intelligent control of livestock environment on the basis of analyzing and collecting information. The control equipment is parallelly connected to the main controller that allows for manual control of the control equipment. According to the

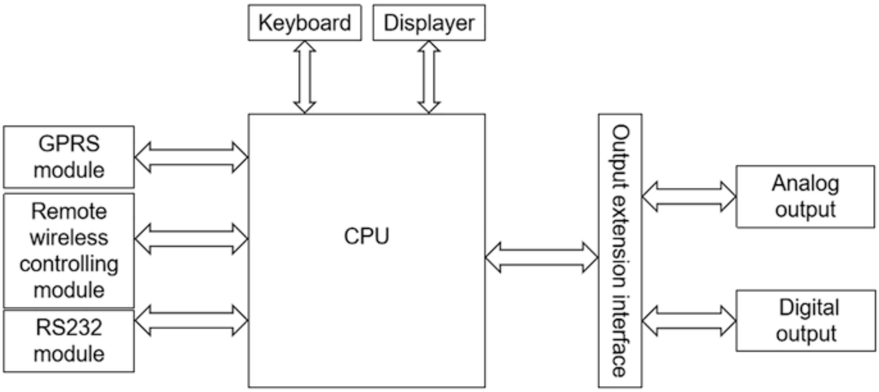

Fig. 12.4 The structure diagram of environment control system for livestock farming

parameters, such as air temperature, humidity, carbon dioxide, hydrogen sulfide, ammonia, and so on, detected by the sensor, the indoor control equipment could be controlled to achieve acquisition of parameters and automatic control. Figure 12.4 is an illustration of the structure diagram of environment control system for livestock farming.

12.2.2.2 Precision Feeding Management System for Livestock Farming

Precision feeding intelligently controls the feeding of fodder in the light of the different nutrient components, contents, and environmental factors required at each growth stage. The functions to be realized by the system are as follows:

Formula of Fodder
The measurement techniques of fodder formula in China's livestock farming, lagging behind those in developed countries, cannot meet the demand of livestock. Tapping into IoT technology and breeding experts' experience, the precision feeding management system established a quantitative model of fodder composition and contents at each stage for different livestock. Additionally, it makes the decisions for precision feeding relying on information on the farming environment and growth state collected by sensors.

Control of Fodder Composition and Content
Based on the establishment of feeding models for different animals, and combined with the actual growth conditions, the intelligent service platform will scientifically calculate the feeding amount and feeding times of the animals in a given day and conduct automatic feeding to avoid human errors.

12.2.2.3 Slaughtering Management System for Livestock Farming

Slaughtering Management

Firstly, the unified and standardized ID code, the crucial link of IoT technology, is utilized to systematically manage the basic information of slaughtering companies, and to supervise the plants' information, hence facilitating centralized management. Secondly, while enclosing the qualified animals for slaughter, the quarantine personnel will inspect the animals entering the waiting pens and record the inspection information, such as inspection date, inspector, cargo owners, quantity, death quantity, existing quantity, urgent killing quantity, and harmless treatment quantity, which will be automatically stored into the system. Thirdly, in the process of slaughtering animals, quarantine personnel could inquire the status of animals waiting for slaughtering through the system, then conduct synchronous quarantine, and supervise the slaughtering companies for quality inspection (refer to Fig. 12.5 for the major features).

Harmless Treatment of Diseased Animal

The harmless treatment of diseased animals covers the basic information of innocuous treatment plants, the mission of centralized plant innocuity, declaration and processing for dead livestock, daily report of innocent treatment, quantity summary of harmless treatment plant, verification for dead livestock and poultry, collection ledger of death of livestock and poultry, disposal transfer receipt for death of livestock, registration of harmless disposal of dead livestock, transport vehicle information of harmless handling, range of vehicle steering, vehicle trajectory monitoring, harmless disposal subsidies, and so on. The system function frame can be found in Fig. 12.6.

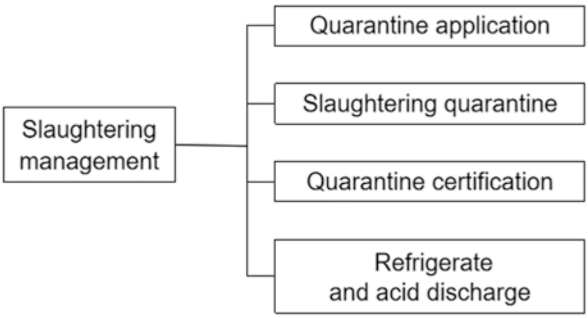

Fig. 12.5 The functional structure diagram of slaughter management module

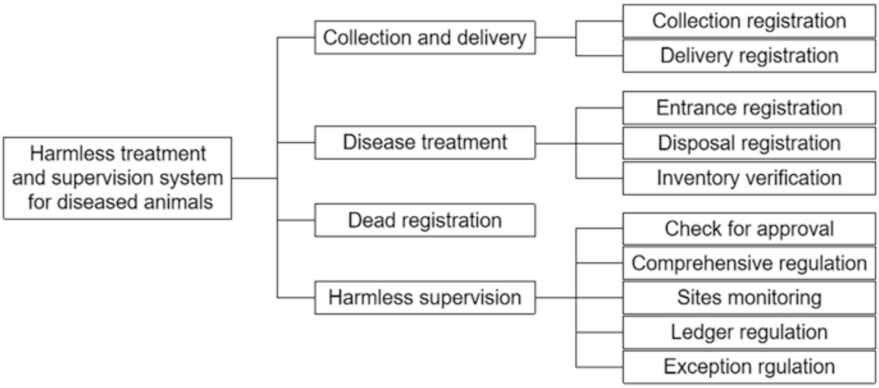

Fig. 12.6 The harmless treatment and supervision of diseased animals

12.2.2.4 Female Reproduction Monitoring System for Livestock Farming

The superiority of the intelligent female reproduction monitoring system lies in improving reproduction efficiency. The reproduction management system mainly includes sensor technology, predictive optimization model technology, and RFID technology. The estrus cycle of female livestock can be scientifically monitored, and precision feeding and digital management can be achieved according to the principle of genetic optimization, thus improving the reproduction efficiency, shortening the reproduction cycle, reducing the number of livestock raised for reproduction, and further lowering down the production costs. The functions of intelligent monitoring of animal breeding mainly include the following aspects.

Estrus Monitoring for Females
Estrus monitoring is an important link in the reproduction process of female livestock. If the right time is missed, reproductive capacity of female animals will go down. To raise the reproduction rate, the number one priority is to monitor the mating period. RFID technology is used to identify individual females, video sensors to monitor their behavior status, and temperature sensors to measure their body temperature. According to the collected data, the system analyzes and determines the estrus information of female livestock.

Female Fodder Management
Pregnant females are identified by electronic tags and are then raised separately in a group environment. Intelligent and automatic feeding (refer to the second section for more details) is conducted according to the precision feeding model and actual conditions of the individual female livestock, so that the growth of female livestock can be effectively controlled.

Database Management of Breeding Livestock
The breeding stock information database ought to be established. The database shall include the individual conditions, reproductive capacity, and immunity status. The database can improve the reproduction capacity of animals and the survival rate of young cubs.

12.2.3 Applications of IoT for Livestock Farming

In the Velos intelligent sow management system, each sow wears an electronic ear tag, which stores all the data concerning their entire life cycle. The amount of feed can be adjusted according to the growth status, activity, breed information, and even seasonal factors. The system recognizes electronic ear tags and controls the automatic feeding mechanism for accurate feeding according to the corresponding feeding curve. This approach avoids fluctuations in sow growth due to inaccurate feeding amounts, feed waste, and stress eating, ensuring that all sows receive the most accurate feed. In addition, the system is equipped with an automatic separator, which separates sick sows, vaccinated sows, estrus sows, and farrowing sows into different areas and marks them in real time. Meanwhile, remote management technology can enable managers in different places to be informed promptly and bring about information-based and modern pig farm management. At present, the Velos intelligent sow management system is widely used, particularly in the Netherlands, a number of European countries, and the United States.

To achieve accurate and intelligent feeding in large-scale farming, it is necessary to be able to identify the individual identity of sows. Velos wears each sow with an electronic ear tag featuring RFID, which is the electronic "identity card" of sows (as shown in Fig. 12.7).

Velos sow feeding station aims at achieving precision feed control of the individual sows. In livestock farming plants, the cost of feed accounts for approximately 35% of the total costs, and the precision feeding of individual sows can help farming plant see their costs reduced. Additionally, physical conditions of sows can be controlled by adjusting the amount of feed. Therefore, automation of feeding delivers tangible benefits to farming plants. Refer to Fig. 12.8 for an illustration of the structure of the feeding station. Adopting advanced sensing technology, image video processing technology, and data processing technology, the Velos estrus monitor enables real-time monitoring of sows and records the identity information of sows that visited boars and the time and duration of visit. Based on the frequency of visits and the time of communication with boars, the employees of the farming plant can render accurate judgment on whether the sow is in estrus and obtain the best breeding time, thereby improving the success rate and reproductive efficiency.

Fig. 12.7 Electronic ear tag

Fig. 12.8 Velos estrus monitor

12.3 Application of Aquatic Agriculture IoT System

12.3.1 The Overall Architecture of the Aquaculture IoT

To bring about information-based and intelligent aquaculture, firstly, various sensors are required for the collection of water quality parameters so as to ensure high water quality for aquatic products. Secondly, the collected information should be transmitted reliably in real time, which demands stable communication conditions. Finally, computer processing system should be used for analysis and decision-making of the transmitted data. In addition, in order to achieve accurate feeding and disease warning, it is necessary to combine IoT technology with image processing methods. This is the case because the precision feeding control and intelligent early warning of disease are enabled by image processing and decision-making. More specifically, images of the remaining bait and the aquatic products are obtained and are then transmitted through communication methods such as Ethernet for processing.

According to the technical support required above, the structure of aquaculture IoT is roughly the same with the average IoT structure, which is divided into three levels: the perception layer, the transmission layer, and the application layer. The structure of the aquaculture IoT system is demonstrated in Fig. 12.9.

12.3.2 Intelligent Water Quality Control System

12.3.2.1 Application Cases of Big Data Cloud Service Platform for Live Pigs During the Entire Industry Chain

Livestock farming, a mega-scale industry, is becoming increasingly important in China's agriculture. In 2013, the total value of livestock farming in China reached 2.8 trillion RMB Yuan, accounting for over 40% of the gross value of agriculture. This makes China the world's largest producer and consumer of livestock farming. For 200 million farmers, tens of billions of animals, and 680,000 veterinarians in China, the amount of data generated is vast and diverse. With the help of deep data mining, the value produced by such data would be immeasurable. Livestock farming is transitioning to data-driven and intelligent production and that the construction of the big data cloud service platform for live pigs during the entire industry chain is essential at this critical stage of the transformation from traditional to modern.

The construction of such a platform was proposed in light of the present situation of information-based development and the project industry development for livestock farming in Zhejiang and Hunan provinces. The data of this project, including the entire business system, underlying data of business platform, industry regulation and service data, and resource data of office business, are encompassed in data

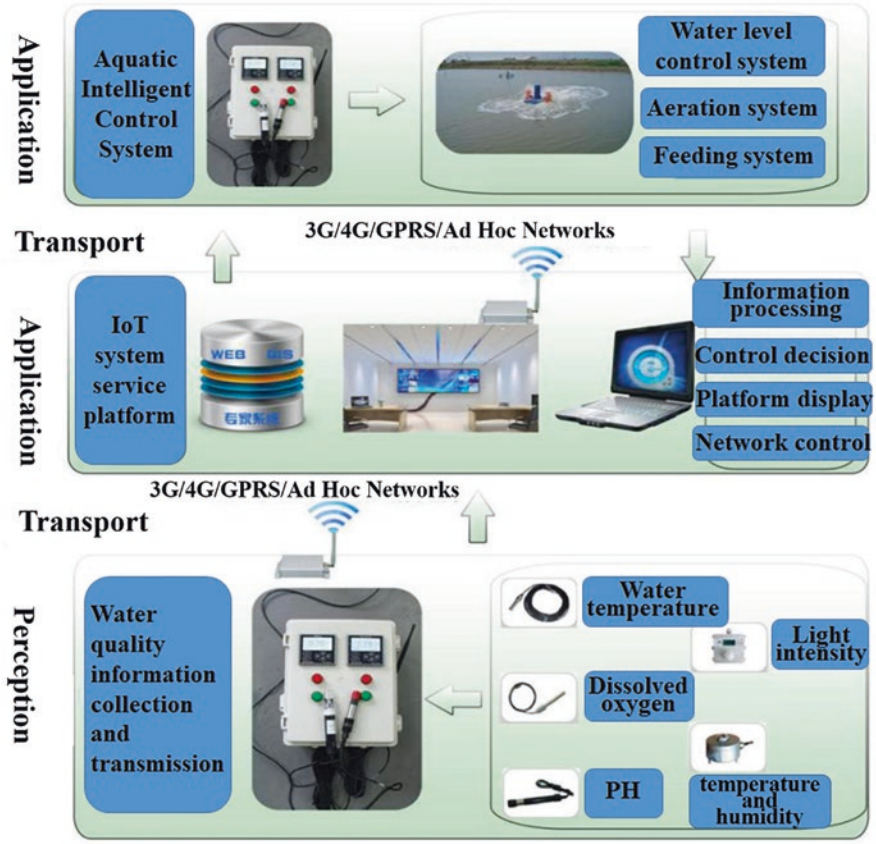

Fig. 12.9 The structure of the aquaculture IoT system

center, which can, at the same time, serve as the basic data platform of the original database and the future business system, covering supervision data, economic data, and business data resources of livestock farming and gradually evolving into a large data center for livestock farming.

Using the safeguard environments for operation, including hardware and software infrastructure, network security, and cloud storage, provided by China Telecom's e-cloud, basic software framework and data standard model are developed and constructed for big data analysis of livestock farming that centers on information collection, data services, and business applications, allowing for the effective integration between supervision administration data and production management data of the whole industry of live pigs and achieving the analysis and application of big data in livestock farming.

Screening is undertaken according to the data dimensions or attributes of multiple categories of the entire live pig industry chain, different performance methods are selected based on business requirements to observe and track the real-time

Fig. 12.10 The schematic diagram of big data display (main interface)

changes of data, and data are thoroughly analyzed to generate searchable and interactive charts that emphasize the presentation of data. Meanwhile, the potential correlation between the data of the entire live pig industry chain is identified to obtain distributed and multidimensional charts. The visualization module can be customized and configured freely (the schematic diagram of which (main interface) is shown in Fig. 12.10). The analysis and supervision system of the entire livestock industry chain covers the supervision of multiple links involving pig breeding, slaughtering, emergency response, and circulation and law enforcement.

Management of Breeding

Management of breeding process covers farm management, data collection management, production process and input management, animal epidemic prevention management, and origin quarantine.

Farm management. Farm management module will be developed and established. Using uniform and standardized ID codes, systematic management will be conducted with respect to such information as enterprise type, enterprise name, production type (breeding type), contact person, contact number, address, legal representative (name, contact number, ID number), industrial and commercial business license, qualification certificate of animal epidemic prevention, harmless treatment facilities, geographical coordinates, farm plans, and so on, so that information-based supervision of farms could be achieved. The geographic locations of the companies involved in livestock farming from all over the world are published on the GIS electronic map. These companies may include large-scale livestock farm households, transport checkpoints, harmless treatment plants of dead diseased animal, fixed points slaughtering companies, fodder production businesses and veterinary drug production and management businesses, and so on (shown in Fig. 12.11).

Data acquisition management. The data of sewage discharge from liquid level sensor, pressure sensor, and flow sensor in the live site of production and breeding can be transmitted to the data processing system through wired or wireless network

Fig. 12.11 Farm management (GIS map display)

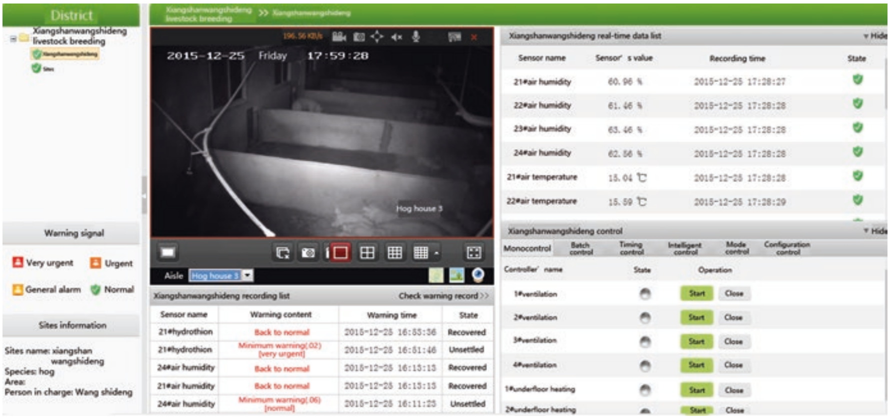

Fig. 12.12 The real-time monitoring of breeding farms

for intelligent analysis and processing. The system can store the past data and build a knowledge base for analysis and processing at any time. When the data related to sewage discharge is abnormal, warning will be given to management staff through short message service, POP window, and music and color warning. Through the platform, the video data of the base can be viewed in real time, and the remote observation of sensor data on the breeding site can be realized by any internet-connected terminal anytime and anywhere. Figure 12.12 is an illustration of the interface.

Production process management is applied to daily production management and statistical analysis of large-scale hog breeding farms. At the same time, it interacts with the higher-level departments for epidemic prevention, quarantine, inspection, etc. Via the process, the necessary production and epidemic prevention data can be uploaded and shared according to the needs of higher-level departments. In addition, the system enables individualized management of the breeding stock. Livestock for sale, associated via ear tags, are managed in batch. The system establishes archives of breeding and epidemic prevention for the particular batch of livestock and gives notice of production, epidemic prevention, and withdrawal period according to the production parameters and immunization programs settings. The system also features operation services such as log-type recording and stage-type economic benefit analysis, owners decision analysis, and application for quarantine, self-checking, and self-verifying for livestock product safety, receiving goods, and interaction with the local regulators. It is noteworthy that the system adopts the B/S mode. While the farm is engaged in production management, the necessary data will be collected and sent to the provincial monitoring data center of livestock farming.

Input management. The safety of fodder and veterinary medicine, the major inputs of livestock farming, is the foundation of the safety of livestock products and the key to ensuring the safety of livestock products from the source. While developing and establishing the input management module, the necessary license information is administered using the uniform and standardized ID code such as the database, geographic coordinates, basic information, and related production and operation license of the production enterprise. The entire-process supervision is achieved, going from company filing, production, sales, and supervision to market supervision and law enforcement, sampling, and release of information releasing.

Animal epidemic prevention management. Epidemic prevention management module is mainly employed by livestock farms, township veterinary stations epidemic personnel, and epidemic prevention supervision departments at all levels. The module is primarily adopted for business management and supervision that covers animal immunization, marking, and so on. The scope of epidemic prevention management module includes pigs, cattle, sheep, chickens, ducks, geese, and rabbits. Breeding stock are quarantined individually, commercial livestock in batch, as are poultry (the batch number determined using ear tags). The batch number of poultry is automatically generated based on the date of birth. The epidemic status of livestock can be registered through app and web terminal, while poultry vaccination status only through the web terminal. Refer to Fig. 12.13 for each module.

Origin quarantine. The livestock will be quarantined at the place of origin when leaving the breeding place, and the process and result of the quarantine at the place of origin will be recorded into the system. Such information will be automatically stored into the system. This process shall be applied to the management of quarantine operations in animal producing areas for the execution of the business processing and supervision of all links of quarantine operations in accordance with ministerial and provincial quarantine regulations. Furthermore, the system achieves a seamless link with the livestock production management system and the designated slaughter quarantine system. It is required that the system shall conform to the management standard of the provincial authority, enable the unified and electronic management of quarantine number, and feature automatic distribution and printing (system functions are as follows in Fig. 12.14).

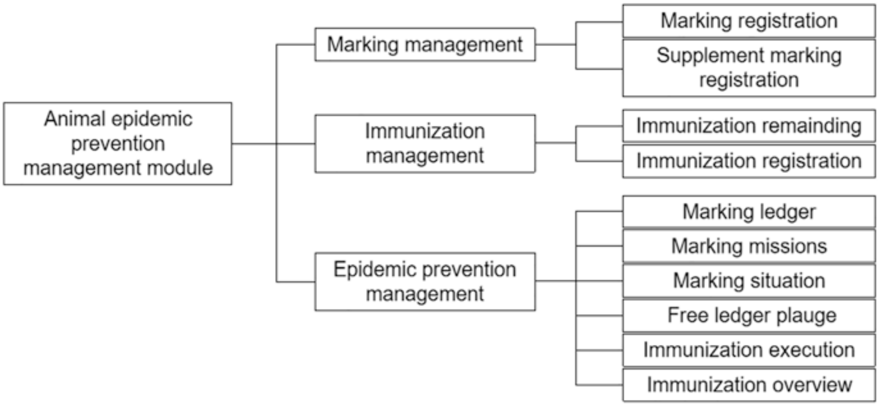

Fig. 12.13 The management module of animal epidemic prevention

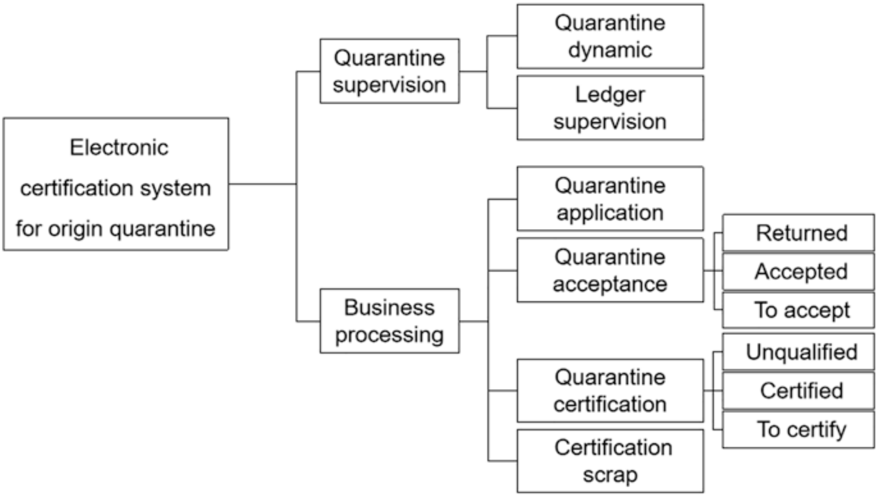

Fig. 12.14 The function diagram of electronic certification system for origin quarantine

Management of Livestock Slaughter

Concerning slaughtering businesses, a series of operations, such as animal admission registration, slaughter declaration, post-mortem inspection, factory registration, retrieving unqualified products, and harmless treatment registration, is enabled with the system. For supervision department, the system allows monthly registration of law enforcement, statistical inquiry of information related to slaughter, and effective linkage with quarantine management (refer to Fig. 12.15 for the interface).

Slaughtering site management. The system allows slaughtering businesses to fill in their basic information and submit it to the relevant authority for review. Moreover, it maintains basic information, supports the upload of business license and other

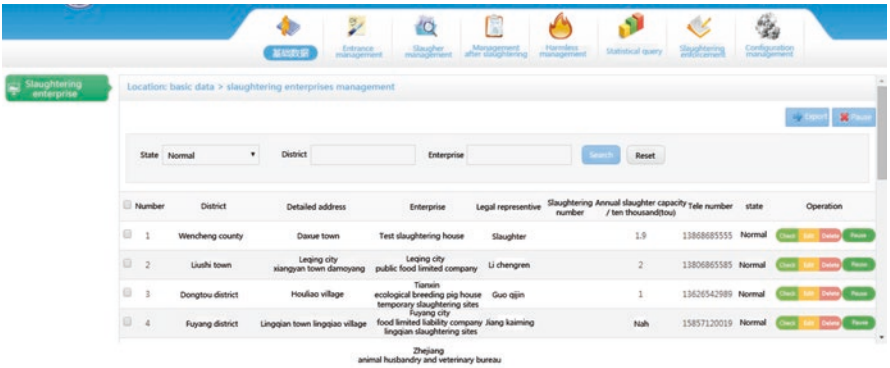

Fig. 12.15 The management interface diagram of slaughtering

credentials, and inquires the progress and details of the application for the record. Besides, the system also ensures that the entity that has been recorded would be able to once again file that record to deal with any change of documents. The records of slaughtering businesses include business numbers generated by system, business name, business type and district (specific to the township and village), detailed address, phone number, corporate information (name, ID number, resume, etc.), contact information of legal person, scale, business license, and self-check laboratory information.

Management of livestock slaughtering. When slaughtering animals, quarantine personnel can inquire the status of animals waiting to be slaughtered through system, then carry out synchronous quarantine on meat productions and sampling inspection of “lean meat essence,” and supervise slaughtering businesses in their meat quality check. For products that fail in quarantine and inspection, harmless treatment would be carried out, which could be automatically recorded into the system. For those passing quarantine and inspection, the quick response (QR) code tracing encoding of the products is printed out using the QR code machine with traceability function matched with the system. The QR code encoding information is automatically uploaded to the system data center, through which the QR code tracing code is linked to the quarantine and inspection information of products.

In accordance with the animal slaughter quarantine regulations stipulated by the Ministry of Agriculture, the system enables the information-based management of businesses in terms of entry inspection, quarantine declaration, pre-slaughter inspection, simultaneous quarantine, harmless treatment, and quarantine result treatment. Additionally, it accomplishes the electronic certification of animal products and the networked dynamic supervision of slaughter and quarantine.

Harmless treatment of diseased animals. Seamless connection and automatic digitalization of all links is possible under this system, covering declaration, acceptance, collection, processing, statistics, and subsidies. The whole process is supervised by the system, from declaration of farmers and confirmation of primary supervision veterinarians and insurance survey personnel, to centralized arrangement and collection of harmless plants, and to the presence of harmless plant personnel and confirmation of harmless treatment. The images are shot and are then monitored and kept, while signatures are collected and uploaded by the handheld terminal. The supervision department, processing center, collection system, insurance company, and farm owner can cooperate in processing, thus making it possible to regulate the whole process of harmless treatment of dead animals and making the data traceable.

Emergency Command Management

Through monitoring of key links, transport vehicles monitoring, emergency command and dispatching, the digital traceability of key links for breeding, harmless treatment, transportation and slaughtering, and the emergency command and dispatching for emergencies can be achieved.

Key links monitoring. Remote command centers are built into three levels, province level, city level, and county level. The video signal is accessed using network and monitoring equipment from supervision object itself to implement the dynamic video remote monitoring for large-scale breeding farms, slaughterhouses, large wholesale markets, the designated crossings of animals and animal products, dispatching supervision and inspection station for animal epidemic prevention, laboratories of animal husbandry and veterinary, harmless treatment, and other regulatory tasks.

Monitoring of transport vehicles. BeiDou or GPS monitoring shall be conducted on fresh milk transport vehicles and transport vehicles in the harmless chemical processing site to track vehicle movement accurately. Through BeiDou or GPS tracking management system, transport vehicles can be fully tracked in real time, and the monitoring center can stay informed of the location and status of vehicles and goods at any time.

Emergency command and dispatching. On the basis of GIS system (Baidu map), the distribution and control of epidemic and safety incidents can be carried out in an intuitive, convenient, and stereoscopic way. Software that enables geographic positioning is relied on to mark the geographic information of relevant places. In the event of an epidemic or a safety incident, the epidemic spot, the epidemic area, the emergent immunization area, and the area designated for handling the incident can be automatically demarcated, marking the intersections that ought to be blocked. Figure 12.16 offers an illustration of the interface diagram of the GIS system.

Management of Sale Links

Management of sales links mainly includes the management of livestock products (pork), trading sites, and market monitoring management, including the management of livestock products business and marketing sites and the management of market monitoring.

Management of sites designated for the sale of livestock products. The management module of points of sale is developed for the information-based management of the basic information of these points of sale. The information recorded into the module mainly include the address of marketing place, person in charge, contact information, business category, relevant certificates, etc.

Fig. 12.16 The interface diagram of GIS system

Management of market monitoring. Daily automatic collection, statistics, analysis, comparison search of price, and short-term, medium-term, and long-term trend prediction analysis of pork price information in the major agricultural products markets of Zhejiang and Hunan provinces are undertaken to provide macro data for meat (hog categories) trading entities and government departments, hence facilitating relevant decision-making.

Management of Supervision and Law Enforcement

Production and management of fodder and veterinary medicine. The management of the production and operation information on fodder and veterinary drugs primarily incorporates the basic information of feed production businesses, veterinary drug production businesses and veterinary drug management businesses, and the reporting functions of the production capacity and the actual production about main products. The system is also equipped with the functions of retrieval, query statistics, and basic maintenance of the abovementioned information, so as to realize the management of the production and operation of fodder and veterinary drugs, and that of product quality monitoring. The information may be submitted by departments at the municipal and county levels or by the corporate entities themselves. The contents of the information can be updated according to the production regulation of fodder and veterinary drugs.

Supervision and management of animal health. The system is applied to the administrative inspection and business management of animal health in supervision institutes of animal health to achieve administrative inspection and supervision within their jurisdiction. The scope of supervision covers breeding farms, slaughtering and processing sites, animal diagnosis and treatment institutions, harmless treatment sites, isolation sites, etc.

Supervision and law enforcement of animal health. This module is applicable to the supervision, law enforcement, and case management of provincial animal health, mainly covering online case handling, manufacturing, and output printing of all kinds of law enforcement documents and other affairs. The module also features inquiry, statistics, and analysis functions. Entry of information in apps on mobile terminals is possible for on-site law enforcement and case investigation. Additionally, video recording of the law enforcement process is also available. To minimize manual input, multiple types of data can be set as dropdown options for selection, or the basic messages can be displayed automatically. Besides, the standard template of documents in each link of case investigation are also provided.

Electronic certification system of animal quarantine includes the administration of real-name registration for electronic certificate and the supervised management of animal health. The system achieves the all-round management of animal health supervision. This system, applied to the management of quarantine operations in production areas, completes the business processing and supervision of all links of animal quarantine in accordance with the ministerial or provincial quarantine regulations.

Quality and safety monitoring of livestock products. The module is used for the sampling and monitoring service of quality and safety for livestock products. The target users include provincial-, municipal-, and county-level supervision departments. They tap into the module to complete the registration of detection for livestock product quality and safety in production entities, such as breeding farms and slaughtering houses. Meanwhile, it is equipped with the function of query, retrieval, and statistics. The diagram of system interface is shown in Fig. 12.17.

12.3.2.2 Water Quality Monitoring System

In large-scale modern aquaculture, the quality of water is crucial to quality, efficiency, and production of aquatic products (Zhang et al. 2011). Water parameters ought to be promptly adjusted to create an ideal environment for growth.

At present, with respect to the monitoring of water quality, a number of physical and chemical indicators of aquaculture water bodies, such as temperature, salinity, dissolved oxygen content, pH, ammonia nitrogen content, redox potential, nitrite, and nitrate, are automatically monitored and alarmed (O'Flynn et al. 2010). The automatic control of water level, aeration, feeding, and other aquaculture systems and the remote monitoring system for multiple environmental factors of aquaculture have also been initially developed. The intelligent control of temperature, pH, and dissolved oxygen, the most common indicators in aquaculture, is of great significance to aquaculture.

Temperature sensors. Fish, shrimp, and other aquatic products are very sensitive to ambient temperature, and inappropriate water temperatures will affect the normal growth and metabolism of aquatic products. Therefore, water temperatures play an important role in the normal growth of aquatic products. Sensitive to temperature changes, temperature sensors can convert temperature information into electrical signals. These sensors are divided into four main types: thermistors, thermocouples, resistance temperature detectors (RTDs), and IC temperature sensors. Among them, the thermocouple features a simple structure and is widely used, but the device has a low detection accuracy. On the other hand, the thermistor comes with high

Fig. 12.17 The electronic certificate demo diagram

detection accuracy and fast temperature response, yet it may cause self-heating due to excessive current.

pH sensors. pH is significant indicator in aquaculture. At present, electrode potentiometric method is the commonly used pH detection method in aquaculture, while the silver-silver oxide electrode is the most common reference electrode. The basic principle of pH sensors is to convert chemical energy into electrical energy and to determine the pH value based on the voltage. Generally speaking, the method is reliable, yet signal drifts do occur in long-term use. In addition to the method

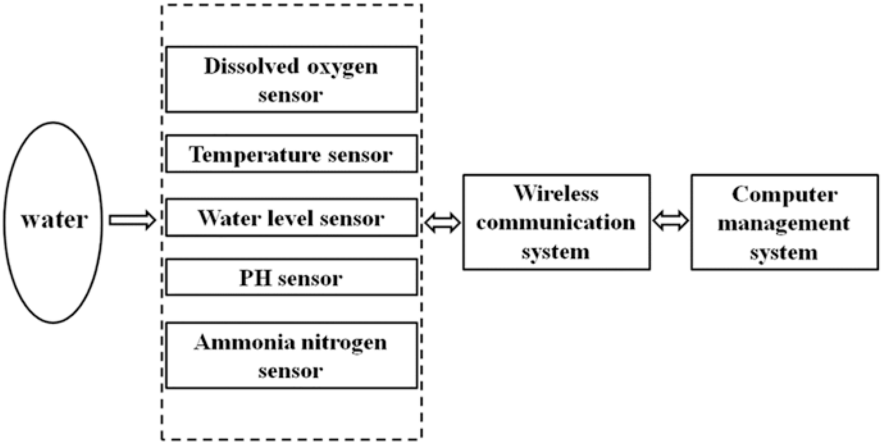

Fig. 12.18 Structure of aquaculture environment monitoring system

listed above, pH values can also be determined via photochemical sensors, pH test paper detection methods, and so on.

Dissolved oxygen sensors. Dissolved oxygen refers to molecular oxygen dissolved in liquid water. For aquatic plants, their survival depends on the amount of dissolved oxygen. At present, the electrochemical sensor is the most common type of dissolved oxygen sensor. The device depends on the detection current to determine the level of oxygen in water. As related technologies mature, optical dissolved oxygen sensors are also gradually applied to the detection of dissolved oxygen. This type of sensors has the advantages of sound stability, high sensitivity, and low drift.

The aquaculture water quality online monitoring system consists of three levels: information acquisition, network transmission, and computer data processing. The overall structure of the system is illustrated in Fig. 12.18. The bottom layer is a data collection node, which adopts a distributed structure. The bottom layer relies on multiple sensors to collect temperature, pH, dissolved oxygen, ammonia nitrogen concentration, and other parameters of the water body and converts the collected data into digital signals. The ZigBee wireless communication module is used to upload the data. The middle layer is the relay node that is responsible for receiving the data uploaded by the data collection node and for uploading the data to the monitoring center through the GPRS wireless communication module. The management personnel monitor the breeding area remotely, thus reducing labor intensity and achieving intelligent and science-based aquaculture.

In order to make the acquisition of information more portable, this design optimizes the water quality acquisition method of the sensing layer. Figure 12.19 is an illustration of the schematic diagram of the pumping structure. The solenoid valve is opened for a period of time and closed afterward. In the water tank, water quality information, such as pH, dissolved oxygen, ammonia nitrogen, and water temperature, is collected by the sensor, the information is then transmitted to the

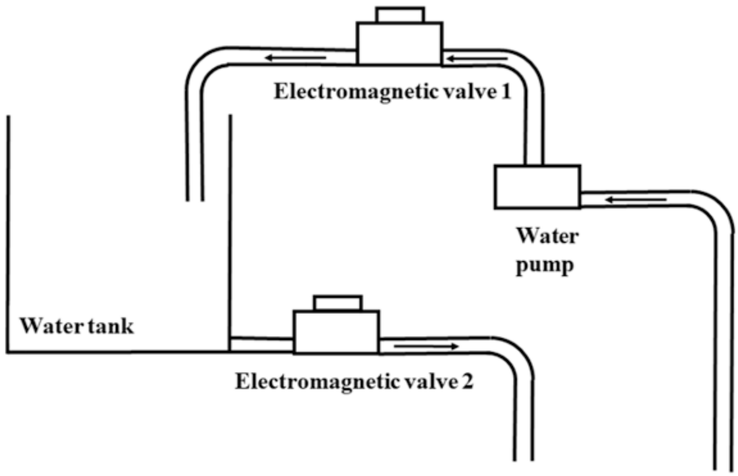

Fig. 12.19 Structure of pumping part

microprocessor, and the acquired data is displayed on the display control screen. Meanwhile, the data is transmitted to the PC in real time through the TCP/IP protocol for remote observation and management. In addition, the collected data will be compared with the predetermined threshold for water quality. If the obtained data exceeds the predetermined range, the system will control external equipment to undertake water quality adjustment. For example, oxygen levels can be increased by opening the waterwheel and the solenoid valve. After information on water quality is collected, the solenoid valve 2 is opened, and after draining for a given period of time, the solenoid valve 2 is again closed.

12.3.2.3 Water Quality Control System

If the obtained water quality index is beyond the normal range, the system adjusts the water quality by triggering the water quality control device until the water quality information returns to the specified range. The regulating devices are mainly aerators, water change solenoid valves, ozone machines, heating devices, etc. Among them, the dissolved oxygen controller is the key to achieving aeration control. It can drive a variety of aeration devices, such as impeller type, waterwheel type, microporous, and aeration air compressor, to improve water quality and to increase oxygen. The solenoid valve is a key device for adjusting water quality, including the adjustment of pH, ammonia nitrogen, and other indicators. Switching the solenoid valve on and off could control the water in and out of the breeding pond, thus maintaining the water quality index within the normal range. Temperature, another major indicator of normal growth, is primarily adjusted by heating devices.

12.3.3 *Aquatic Disease Warning System*

12.3.3.1 Disease Early Warning System Based on Machine Vision Technology

This system, based on image processing technology and IoT technology, includes perception layer, transmission layer, and application layer. Among them, the perception layer is mainly composed of industrial cameras, stepper motors, and aquatic product observation platforms, as shown in Fig. 12.20. The basic working principle is that the underwater observation platform is lifted by a motor through a rope. After being pulled to a certain height, the camera works to obtain the platform image information directly below it and transmits the image to the application layer through Ethernet. The disease identification model determines the number of aquatic products that are ill or dead and sends a signal to the warning light to urge the breeder to deal with the breeding pond in a timely manner. Figure 12.21 illustrates the working flowchart.

The specific method for implementation of the system is given below. To begin with, the timing of the motor is controlled by the internal clock switch of the main control board (timing can also be achieved through the display control screen). The motor rotates forward at certain intervals and pulls the observation platform from the bottom of the pool at a constant speed. Since most aquatic products, including vannamei and fish, will perish rapidly after leaving the water, the height should not be set too far from the surface of the water. Therefore, the appropriate observation platform height is selected according to the stretching height and motor rotation speed. After reaching a certain position, the motor stops rotating, and the industrial camera obtains the platform image and transmits the collected image information to

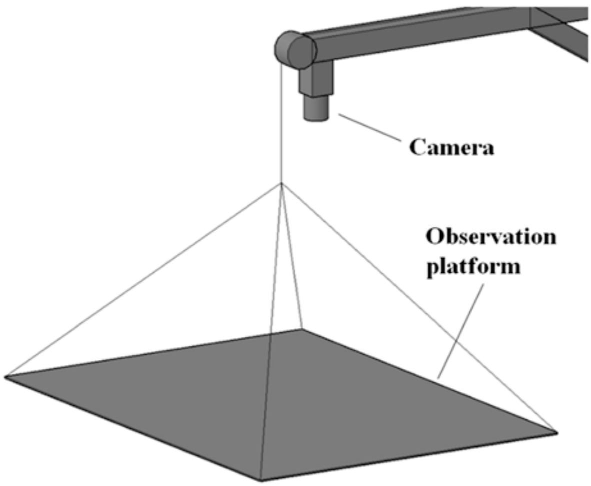

Fig. 12.20 Perceptual structure

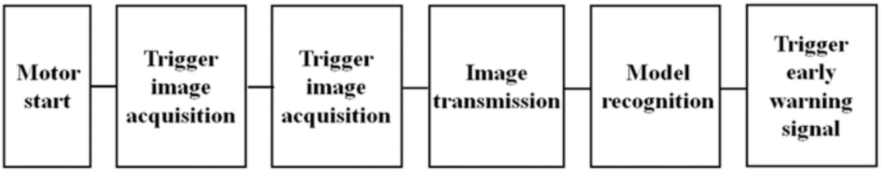

Fig. 12.21 Work flow chart of aquatic disease early warning system

the application end via Ethernet. Based on the established model, whether there is a diseased or dead shrimp can be determined. Such information is used as an early warning signal for breeding, which is available to breeders through PC or mobile terminal.

The functions of the machine vision system mainly include image background segmentation, image feature extraction and optimization, classifier application, data communication between upper computer and lower computer, etc. Primarily, it works through the trigger attribute that comes with the camera. The camera is triggered by combining the switching of the motor on and off with the code in the SDK software development kit. Only one image can be obtained per collection. Through image morphology and classification algorithms, the system achieves shrimp and bait extraction, identification of dead and dead shrimp, and bait recognition. With regard to the application and selection of classification algorithms, the effect of traditional machine learning algorithms and convolutional neural networks (CNN) on the classification of dead vannamei is taken into consideration. Eventually, the identification of dead shrimp and bait identification of vannamei is achieved, and an alarm signal is triggered to remind the staff to intervene and activate the automatic bait feeder.

12.3.3.2 Classification of Sick and Dead Shrimp Based on Image Processing

Based on the color difference between healthy and dead vannamei, and between body and background, healthy vannamei are extracted using the image gray value difference method. Figure 12.22a shows the effective area of the intercept. First, a grayscale histogram of the image is drawn, in which the abscissa represented the gray value and the ordinate represented the number of pixels corresponding to the gray value. The figure reflects the distribution of image gray values in a simple and intuitive manner. Three representative shrimps were selected for analysis, and other samples also demonstrated similar color characteristics. By analyzing the histogram, it was found that when the selected segmentation threshold was 100, the target and the background could be well-segmented. The area where gray value was smaller than 100 was set to 0; otherwise, the gray value was set to 1. Refer to Fig. 12.22b for the ROI image. Then the image was processed by dilation algorithm to eliminate the small and smooth objects. The canny edge detection algorithm was

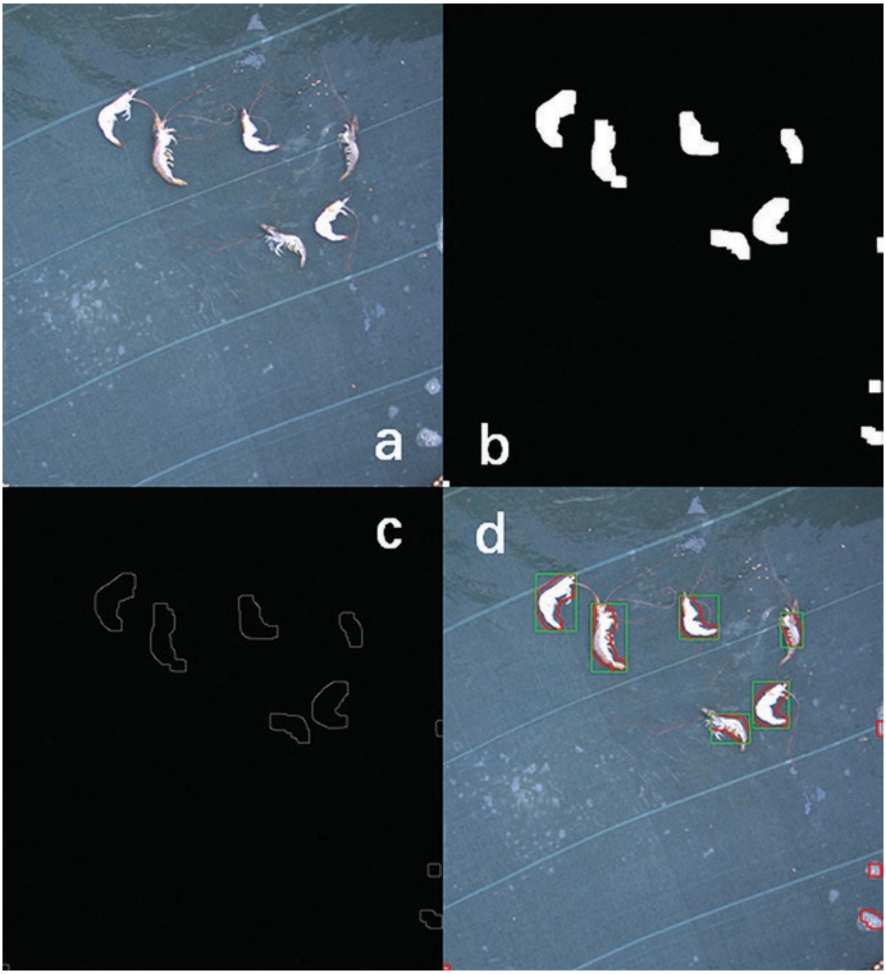

Fig. 12.22 Morphological processing of *P. vannamei*. (**a**) Effective area intercepted, (**b**) binarization, (**c**) target outline, (**d**) original image target selection

relied on to extract the contour of vannamei, as shown in Fig. 12.22c. Processing flow of the algorithm mainly includes the following five steps:

- Smoothing and denoising via a Gaussian filter
- Calculating the gradient intensity and direction of each pixel in the image
- Applying non-maximum suppression to eliminate the spurious response caused by edge detection
- Applying double-threshold detection to determine the real and potential edges
- Completing the edge detection by suppressing isolated weak edges

Finally, the leftmost, rightmost, uppermost, and lowest pixel coordinate positions are obtained according to the extracted edge contours. In order to ensure that the outline of the shrimp could be included in the selected rectangle, the rectangular area was extended by 20 pixels on the left and right and by 50 pixels upward and downward. The finally obtained selected area is illustrated in Fig. 12.22d.

Logistic Regression (LR)

Logic algorithm, simple, efficient, and easy to parallel, has been extensively adopted in many fields. As an online learning algorithm, it can use new data to update various features without the need to re-train past data. By introducing the Sigmoid function in the linear regression model, logistic regression maps continuous output values from the uncertain range into the (0,1) range. This becomes a probabilistic prediction problem. Its objective function is:

$$h_\theta(x) = g\left(\theta^T x\right) \tag{12.1}$$

The definition of the Sigmoid function $g(z)$ is as follows:

$$g(z) = \frac{1}{1+e^{-z}} \tag{12.2}$$

One method commonly used in statistics is maximum likelihood estimation (MLE), which finds a set of parameters so that the likelihood (probability) of data would be greater. There are multiple solutions that could address this optimization problem. Gradient descent, also known as the fastest gradient descent, is an iterative method. The optimal value is approximated by selecting the direction of the parameter that makes the objective function change the fastest at each step.

In this chapter, logistic regression is used to differentiate healthy shrimp from dead shrimp. The sample set of normal shrimp and diseased shrimp were 9352 and 9197, respectively. As a result, the fit score of the classification model (fit score) was 0.92.

Convolutional Neural Network (CNN)

Computing capabilities have grown rapidly in recent years; as a result, convolutional neural network algorithms also matured at a high speed. Featuring unique advantages, the algorithm has been widely used in research on image recognition, target classification, and so on. Common convolutional neural network algorithms mainly involve input layers, convolutional layers, activation functions, pooling layers, and fully connected layers.

The crucial role of the convolution layer is to extract features from the input two-dimensional data. A convolution kernel of a suitable size, also known as the filter or a square matrix of $N \times N$, is set, and its depth is consistent with the data of the input layer. The convolution kernel and the input layer data are continuously dot-multiplied to obtain new data as the next input.

The pooling layer changes the size of the image, a form of down-sampling. Convolutional networks are equipped with multiple forms of nonlinear pooling functions: average pooling, maximum pooling, etc. The max pooling is applied in this chapter. The size of the pooling is 2 × 2. The maximum pooling is essentially a process of filtering features. At the same time, the pooling layer will continue to reduce the size of data. Therefore, the number of parameters and calculation will also go down, avoiding overfitting to a certain degree.

Currently, the popular activation functions include sigmoid, tanh, relu, leaky, etc. Relu is used as the activation function here (Nair and Hinton 2010). Relu has its own advantages. First, it is free from vanishing gradients. Second, it increases network sparsity. Third, the computational complexity is small. Relu is expressed as:

$$f(x) = \max(0, x) \tag{12.3}$$

Figure 12.23 is an illustration of the function image.

The dropout layer plays a significant role in deep networks. As the number of network layers increases, the number of parameters increases rapidly, leading to overfitting. What is meant is that the network cannot generalize new data well and the difficulty of network training will significantly ramp up. The holding probability is between 0 and 1, usually between 0.2 and 0.5, and the probability p was set to 0.25 in this article.

When the above steps are executed, the convolution-activation-pooling-dropout loop process is completed. What this means is that all the features are connected through the fully connected layer, and the output value is finally sent to the classifier.

In this chapter, Conv (3 × 3 × 16) was used, which was a convolution layer. The 16-channel filter size was 3 × 3. Stride (1,1) was selected, which represented that the step size of the convolution process was 1. Maxpooling (2 × 2) was selected, which meant that it was a maxpooling layer with 2 × 2 filters.

In this sample set, the normal shrimp body and the diseased shrimp body were the same as above, 9352 and 9197, respectively. Each training reads 32 pieces, all of which were repeated 30 times. It was found that when cycling times was eight, the classification accuracy reached 92.03%, and the loss value was 0.2316.

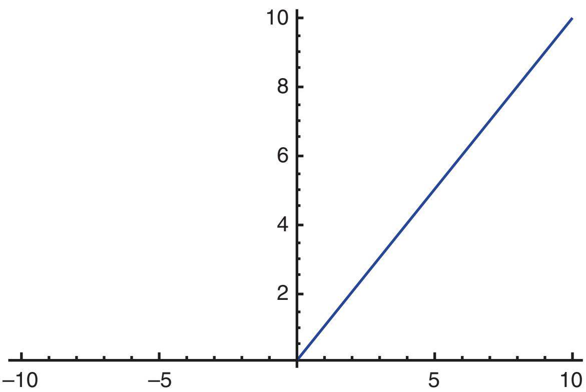

Fig. 12.23 Relu function

12.3.4 Precision Feeding System

12.3.4.1 Introduction of Precision Feeding System

Feeding methods is critical to aquaculture – improper feeding methods can result in wasted resources, and excessive feed may contribute to eutrophication, which causes pollution to aquaculture waters and brings unnecessary economic losses.

To achieve precision feeding, the model of the quantitative relationship among the growth stage, the feeding rate, and feeding amount should be established based on relationship between length and weight of aquatic products. Moreover, the relationship between the length and weight of each breed needs to be analyzed. Likewise, the relationship among external factors, such as light intensity, water temperature, dissolved oxygen content, turbidity, ammonia nitrogen and breeding density, and the absorption capacity and nutritional intake of fish bait, should be analyzed. By doing so, demand-specific feeding is achieved, and the loss of bait and costs are reduced.

In this chapter, a precision feeding system based on image processing technology is applied. The image acquisition method, the same as the aquatic disease early-warning system, is achieved by starting the motor to pull up the observation platform and triggering the camera to work. The acquired image is transmitted to the application through Ethernet. The remaining bait is discriminated and counted by the established model, which is used as the basis for determining the hunger levels of aquatic products (*P. vannamei*, fish, and so on). According to the remaining amount, the amount of bait is adjusted to achieve precision feeding.

12.3.4.2 Method for Identifying and Counting Bait Based on Image Processing

There are two types of targets in the image: bait and shrimp. In order to distinguish the two targets and identify the bait, this article completed the segmentation of bait targets based on the HSV color space of the image. In particular, H values represent hue, S values represent saturation, and V values represent brightness. Unlike the RGB color space, the HSV color space features an inverted cone model. The angle represents hue, the saturation represents the distance from the point to the central axis, and the brightness represents the position on the central axis. The ranges of the three components in OpenCV are H: 0 ~ 180, S: 0 ~ 255, and V: 0 ~ 255. Compared with the RGB color space, the HSV color space can reflect the hue, brightness, and vividness of image colors in a more intuitive manner.

Gaussian filtering, used in this chapter, is a common linear filtering smoothing algorithm. The goal of its adoption is to filter out Gaussian noise, which is a kind of noise with a probability distribution showing a Gaussian distribution. Gaussian filtering determines the parameter weights according to the shape of the Gaussian function to achieve smooth filtering. Figure 12.24 shows one-dimensional and

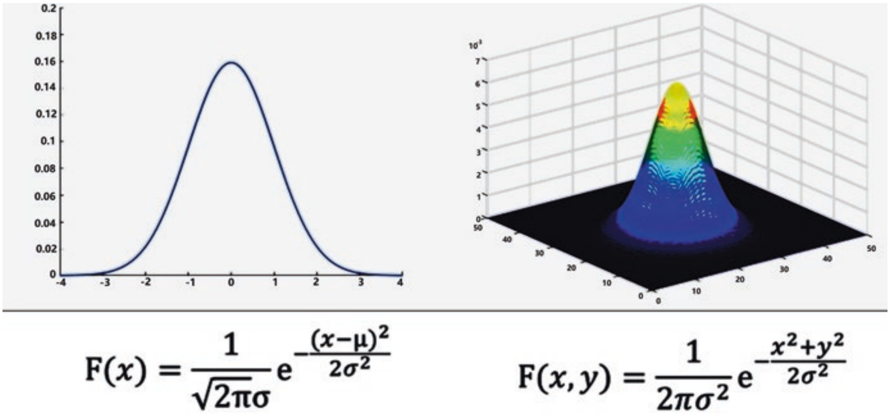

Fig. 12.24 1D and 2D Gaussian distribution functions

two-dimensional Gaussian distribution function graphs. The bait target could then be acquired according to the HSV threshold segmentation method. The image was binarized and then processed by the dilate algorithm. Target edge was processed by Canny algorithm. The processing results are shown in the Fig. 12.25. The remaining amount of bait was determined by calculating the number of targets.

This system is mainly designed for the breeding of pearl gentian grouper (hybrid of tiger grouper and gentian grouper). This intelligent management and control system are primarily involved with the water quality control of aquaculture ponds and ultraviolet sterilization ponds. In particular, one of the aquaculture ponds is selected as a demonstration pond. Major indicators of the system include pH, dissolved oxygen, and ammonia nitrogen. Data on water quality is obtained in real time to determine the "health status" of water quality. When the pH value is not within the normal range, the switches of the water inlet and outlet solenoid valve will be triggered to speed up the water change. When the dissolved oxygen value is not within the normal range, the aerators will be activated. When the ammonia nitrogen value of the tail water is not within the normal range after treatment, it will be indicated that the treatment effect of the purification cycle system failed to reach the requirements and the breeding personnel are prompted to cope with the situation in time.

12.3.4.3 Land-Based Multi-Niche Circular Aquaculture System

Based on the theory of niche complementarity, the land-based multi-niche circular aquaculture system forms an ecological circular aquaculture mode through species of different nutritional grade and achieves the goals of high efficiency, safety, energy efficiency, and emission reduction by optimizing the systematic aquaculture capacity and via control measures.

The system locates on the coast of the East China Sea in Longwan District, Wenzhou City, Zhejiang Province, China. The aquaculture base where the system is

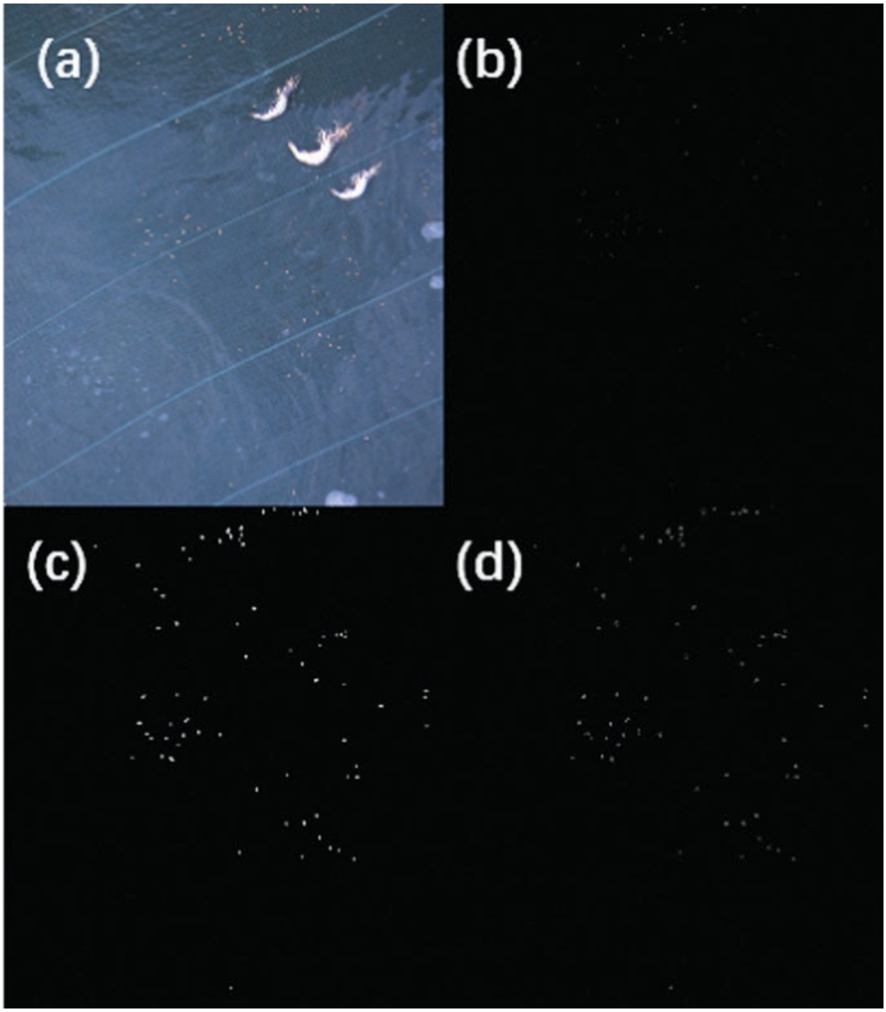

Fig. 12.25 Target processing results. (**a**) The original image, (**b**) binarization, (**c**) dilate process, (**d**) edge extraction

at covers a total area of 276 acres and is composed of five functional areas and two supporting systems. The five functional areas are high-level intensive cultivation area, seed breeding area, shellfish breeding area, plant cultivation area, and ecological purification area. The two supporting systems are circulating water channels and online water quality monitoring systems.

The tail water from the breeding area and high-level intensive culture area collects most of the bait and feces through the tail water treatment system, and the rest flows into the various shellfish breeding ponds through the circulation channel. First, the microalgae and organic debris in the water are removed by the shellfish filter-feeding function in the shellfish culture area. It then flows through the circulation channel into the planting area. Thirdly, through further biological, physical, and chemical purification, it flows into ecological purification ponds. After a period of time, water enters the underflow wetlands. Then, after the zooplankton and algae are settled in the water, it is pumped into the sand filter. Finally, it flows back into the greenhouse and high-level intensive culture areas.

By tapping into the multi-nutritional coupling effects of fish, shrimp, shellfish, algae, and salt-tolerant plants, the system maximizes the use of materials and energy in the system and delivers economic benefits. In addition, because the aquaculture water is recycled in the system, there is no need to inject water from external sources, hence reducing the dependence on the external environment and the ecological impact caused by sewage.

The risk of vannamei farming is relatively high, primarily because of the lack of precise monitoring and intelligent control equipment, particularly in high-density farming environments. Dissolved oxygen is the key to the survival of shrimp, as hypoxia can easily cause suffocation, while oxygen enrichment easily increases the risk of waterborne bacteria and infections. Therefore, the system developed an online water quality monitoring system and automatic control equipment to achieve online monitoring and control of water quality in the culture pond. The designed control scheme is illustrated in Figs. 12.26 and 12.27. The control instructions of the monitoring center are mainly based on the real-time information received from the fishing pond IoT and are sent to the controller through communication. The controller executes the operations of automatic oxygen increase, automatic drainage, and water supply according to the control commands. The principle is shown in Fig. 12.28. In addition, when combined with machine vision technology, it achieves identification and early warning of sick and dead shrimp and accurate feeding of bait.

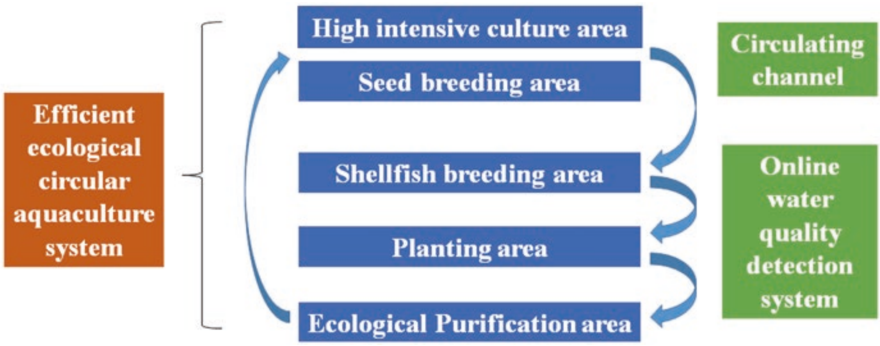

Fig. 12.26 Land-based multi-niche cycle breeding system

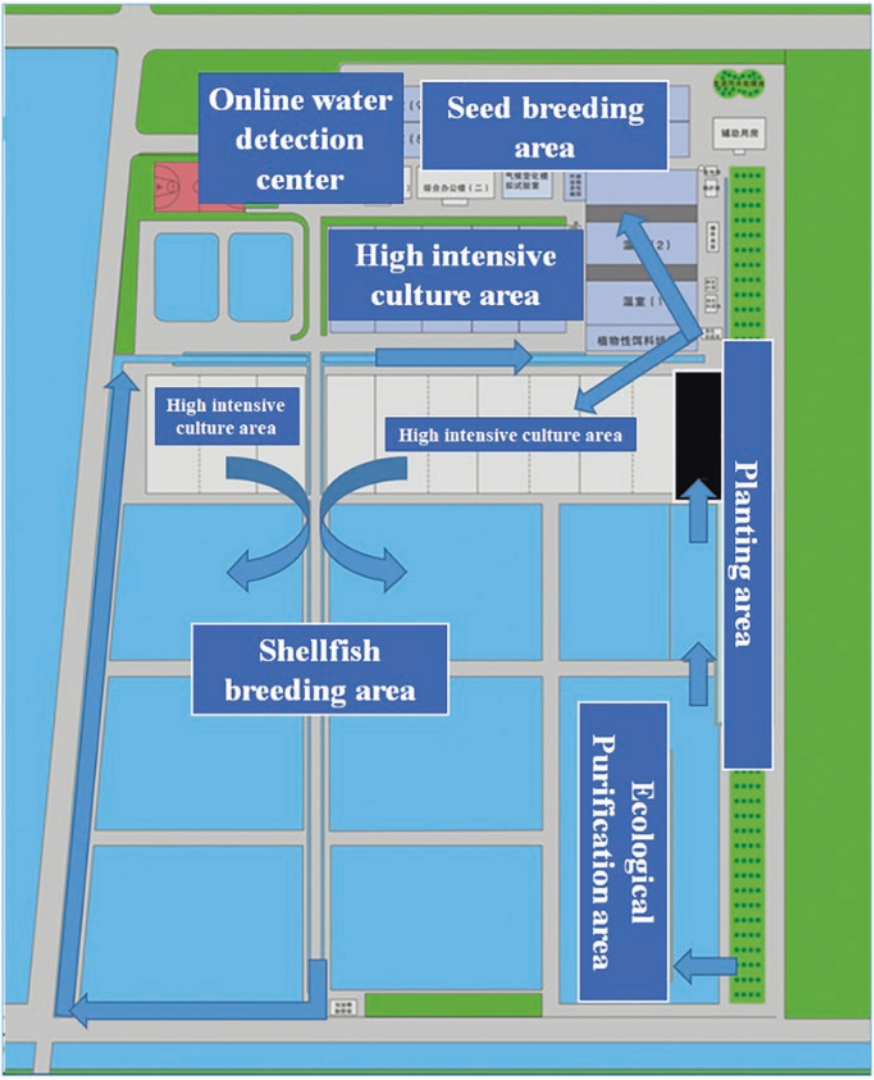

Fig. 12.27 Land-based multi-niche cycle aquaculture system

12.3.5 *Circulating Aquaculture System*

The industrial aquaculture system with recycling water, available at Dongtou Base, Zhejiang Aquaculture Research Institute, China, is mainly composed of aquaculture ponds, curved screens, pumps, sedimentation tanks, biological purification tanks, protein separation tanks, UV sterilization tanks and aeration tanks, etc. Figure 12.29 offers an illustration of the system.

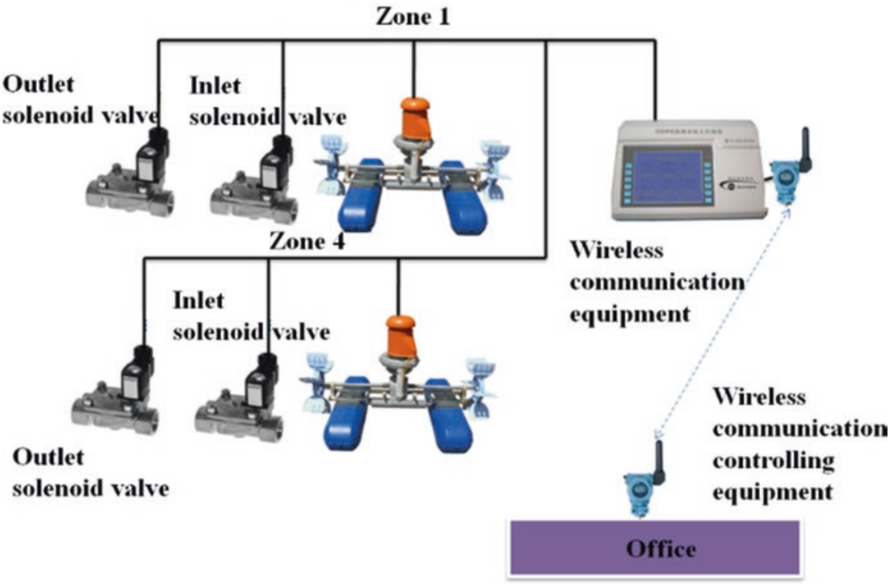

Fig. 12.28 Automatic aeration and water exchange of IoT

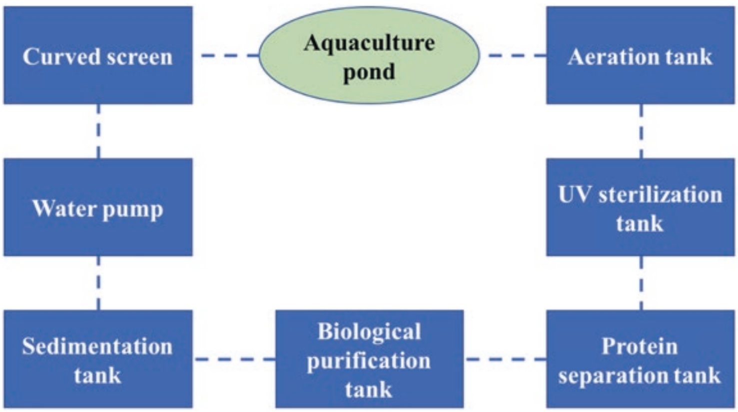

Fig. 12.29 Circulating water industrialized aquaculture system

12.4 Summary

Livestock farming and aquaculture are the major components of modern agriculture. Modern livestock farming and aquaculture is no longer limited to the modernization of the breeding process. It has evolved into the modernization of infrastructure, the modernization of management, the modernization of living and consumption, the modernization of resources and environment, and the modernization of science and technology. All these require the support of modern science and technology, especially that of modern information technology.

As a highly integrated information technology with comprehensive application, IoT has become one of the commanding heights of a new round of economic and technological development. The development of IoT technology has provided opportunities for the information-based growth of modern livestock farming and aquaculture, while aquaculture provides an application platform for the development of IoT technology.

Using sensor technology, wireless sensor network technology, automatic control technology, machine vision, radio frequency identification, and other modern information technologies, the livestock farming IoT system monitors the environmental parameters of livestock in real time. Additionally, the system rationally controls the environment of livestock farming according to the growth needs of livestock. The system allows automatic monitoring of livestock environment, fine feeding, breeding, slaughter management, and digital sales management.

Aquaculture IoT systems play a major role in aquaculture. It has transformed the traditional approach of heavy consumption of resources and extensive management in aquaculture, made possible the monitoring of the water quality and environment, and addressed the problems of the water quality deterioration caused by improper feeding and excessive drug use. Aquaculture IoT systems improve the quality of aquatic products and reduce the incidence of aquatic diseases. Relying on such systems, issues relating to aquatic product quality and aquatic environment pollution can be addressed, hence improving people's livelihood.

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Chapter 13
Agricultural Products Traceability System Applications

Pengcheng Nie, Yong He, Na Wu, and Hui Zhang

Abstract Against the backdrop that food safety has become an increasing public concern, both national policies and technologies facilitate the building of a food traceability system, whose application has become more and more popular. Thanks to the wide application of agricultural IoT, information about the production, processing, logistics, and market circulation of agricultural products has been collected more thoroughly. Consumers can find out about product information by scanning the traceability code, thereby increasing consumer trust. This chapter lays out an introduction about the application of the agricultural IoT in agricultural products traceability from the aspects of individual identification technology, traceability system structure, and application in planting, livestock farming, and aquaculture.

Keywords Individual identification technology · RFID · Bar code · Two-dimensional code · Agricultural products traceability system

13.1 Introduction

The International Organization for Standardization (ISO) (8042: 1994) defined "traceability" as "the ability to trace the history, application or location of an entity by means of recorded identifications" (Karlson et al. 2013). According to the Codex Alimentarius Commission (CAC), traceability is defined as the ability to position food at any given stage in its production, processing, and distribution processes. Olsen and Borit (2013) defined traceability as "the ability to access any or all information relating to that which is under consideration, throughout its entire life cycle, by means of recorded identifications." Specifically, traceability includes two aspects. One is to trace back, that is, to trace the process of food and its components along the production chain, hence establishing a circulation history. The second is to trace

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forward, i.e., to trace the food and its components in the production chain. Tracing forward is primarily used to retrieve risky food (Chen 2017). As the trade on food globalizes at ever-faster pace, issues in food safety have occurred frequently. In order to reduce production costs, certain unscrupulous merchants have been engaged in all sorts of fraudulent acts to deceive consumers, including falsification of product origins and adulteration of products. Frequent market fraudulences damage both consumer health and the reputation of local brands and specialty agricultural products. Nowadays, consumers wish, more than anything else, that the quality of food could remain true to their product description and that more information on product origin could be made available. Therefore, traceability of agricultural products is regarded as an essential element to ensure food safety and high quality (Tang et al. 2020).

The purpose of establishing a traceability system is to standardize agricultural production, ensure food safety, enhance technological levels, stimulate brand competition, maintain normal market order, and crack down on counterfeiting and adulteration. This significance of building such a system is that companies can better implement brand and premium strategies, achieve high value-added production and sales, build brand image, enhance corporate value, and connect production, circulation, and management processes. Additionally, they can also provide comprehensive information-based solution of the entire industrial chain and offer reference models and standards for agricultural product standardization and data management. With regard to the government, a traceability system would be conducive to improving the quality control, supervision, and circulation and export trade of agricultural products. Moreover, it would also help standardize the inspection of products. As such, the government is in urgent need of a food traceability system, through which food quality and safety-related information can be acquired for effective supervision, thus improving the effectiveness of supervision and reducing the probability of food safety incidents. When problems do occur, the reasons and accountabilities could be quickly investigated and determined. With respect to consumers, a traceability system would keep consumers informed of relevant product information. In light of the status quo of food safety and the awakening of consumer awareness, consumers should have the right to make informed. A new understanding of food safety is born, and that food safety ought to be reviewed and evaluated from a scientific perspective. The adoption of a food traceability system could eliminate information asymmetries, protect consumers' right to be aware, and enhance public confidence in food (Bosona and Gebresenbet 2013).

The reason why the modern food quality and safety traceability system has been valued and developed rapidly is considered to be the "bovine spongiform encephalopathy (BSE)" crisis since the 1990s, the dioxin contamination that swept Europe, including Denmark and Belgium, and food safety incidents such as the *E. coli* crisis (Pettitt 2001). In 2002, at the meeting of the CAC Intergovernmental Task Force on Food and Biotechnology (Food Traceability System), a number of EU countries proposed a food quality and safety information management system, which is aimed at controlling foodborne hazards, protecting consumer health and ensuring fair trade. Compared with developed countries in the European Union, the establishment of agricultural traceability systems in Asia started relatively late, and most countries are still in the infancy of such constructions. Among the Asian countries, Japan was the earliest one to develop the traceability system of agricultural products. From 2001 to 2005, Japan brought into reality the concept of a traceability system of agricultural product quality and safety. However, India, a major agricultural country, only began to explore the concept and establish related systems in 2006. South Korea also followed this trend and started the development of traceability of agricultural products in 2005 (Feng et al. 2014). The concept of traceability of agricultural product quality and safety in China was proposed by the agricultural department in 2002. In the 2 years following that, China have formulated relevant policies for the traceability of agricultural products and provided corresponding technological support (Zhao 2018). The construction of China's agricultural product quality and safety traceability system began in 2004. It was first implemented in Beijing and Shanghai as a pilot project. After successful implementation, it began to be promoted to other provinces and cities. So far, many provinces and municipalities have set up traceability systems of agricultural products, covering fruits and vegetables, as well as livestock, poultry, and aquatic products.

As time goes by, consumers and merchants are paying more attention to food safety issues and the establishment and maintenance of brands. Under such a background, both national policies and technologies have facilitated the creation of a food traceability system. Greater efforts have been made in this regard, and the application of the system have become increasingly popular. If a traceability system for agricultural products is established, once a safety problem that endangers human health is discovered, the location of the hazard can be determined by reverse research based on information recorded in the entire process from the supply of raw materials to the consumption of the finished product, and the hazard can then be controlled and blocked from the source. At the same time, the product flow can also be tracked forward, and unsold foods can be promptly retrieved to prevent any possible escalation of the problem, thus protecting the health of consumers and minimizing economic losses. Through the establishment of this system, government or risk managers can also achieve science-based and effective supervision. Owing to the adoption of new technologies such as big data, cloud computing, and the IoT in agricultural and food production, more comprehensive information can be collected and analyzed, and timely and reliable information transmission channels between producers and consumers can be established to build stronger consumer trust. Meanwhile, information collection and analysis can in turn generate more positive feedback for improving the quality and efficiency of production and for saving production costs in all aspects. Based on the above reasons, food traceability has become a focal point in research that ensures and improves food quality and safety.

13.2 Individual Identification Technology

13.2.1 Principles and Applications of RFID Technology

13.2.1.1 Principles of RFID Technology

RFID radio frequency identification is a wireless communication technology that can automatically identify target objects and read and write data through radio signals. As a noncontact automatic identification technology, the identification process does not require manual intervention; RFID radio frequency identification can withstand multiple types of harsh environments, including severe shock, vibration, electromagnetic environments, extreme temperatures, and chemical corrosion. In addition, RFID technology can be used to identify objects that are moving at a high speed and to read multiple tags in batch. Furthermore, the technology is fast and convenient to deploy.

An RFID system usually consists of a tag, a reader, and an antenna:

- The tag, also known as transponder, consists of a tag chip and a tag coil. Each tag stores a unique electronic code and is attached to the object to determine the item-level target object code.
- The reader is a device that reads or writes tag information. Consisted of a radio frequency module and a signal processing module, the reader usually features a handheld or fixed design.
- The antenna is a device that establishes a wireless communication connection between the tag and the reader to achieve the spatial propagation of radio frequency signals.

The basic working principle of RFID technology is that when the tag enters the reader's magnetic field range, the microchip circuit is activated by the energy obtained by the induced current. The chip converts the electromagnetic waves and then sends out the stored product information (passive tag). Or the tag would use the battery installed in the tag to provide energy to actively send product information stored in the chip (active tag). The interpreter decodes the received product information and sends it to the central information processing system for data processing, hence achieving management control.

Some systems are also connected to an external computer (upper computer's main system) through the RS232 or RS485 interface of the reader for data exchange.

The specific working process of the system is as follows: the reader sends a certain frequency of radio frequency signals through the transmitting antenna to form an electromagnetic field area, which is its working range. When the electronic tag enters the magnetic field area of the transmitting antenna, an induced current will be generated due to space coupling, and the electronic chip microchip circuit will be activated to obtain energy. When activated, the electronic tag modulates such data as its own code onto the carrier and sends it out through the card's built-in transmitting antenna. The receiving antenna of the reader receives the carrier signal sent by the electronic tag and transmits it to the reader. The data processing circuit demodulates and decodes the received signal containing data information and then sends it to the background system for further processing. After the main system confirms that the card is legitimate through logical operations, it makes corresponding judgments and commands according to different pre-settings and then sends instruction signals to control the executing agency to perform corresponding operations.

Fundamental differences exist between different contactless transmission methods in terms of coupling methods, communication processes, frequency ranges, and data transmission methods from RF cards to readers. However, all RFID systems are similar in their basic principles and design structures. All readers can be regarded as consisting of two main modules, namely, a high-frequency interface and a control unit.

The high-frequency interface works to generate high-frequency transmission power that provides energy to activate the electronic tag. It modulates the transmitted signal and sends related data to the electronic tag. Furthermore, the interface receives the high-frequency signal sent by the electronic tag and completes demodulation. Refer to Fig. 13.1 for the schematic diagram of the high-frequency interface of the inductive coupling system.

The control unit enables the communication with the application system software and receives and executes the commands it sends. It is additionally responsible for the encoding and decoding of signals and the related control of the communication process with the electronic tag (master-slave principle). In the event of extraordinary circumstances, such as conflicts and interference caused by overlapping working areas of readers, the unit deploys anti-collision algorithms. Apart from this, it is responsible for the encryption and decryption of related data transmitted between the electronic tag and the reader, as well as the identification of the electronic tag and the reader.

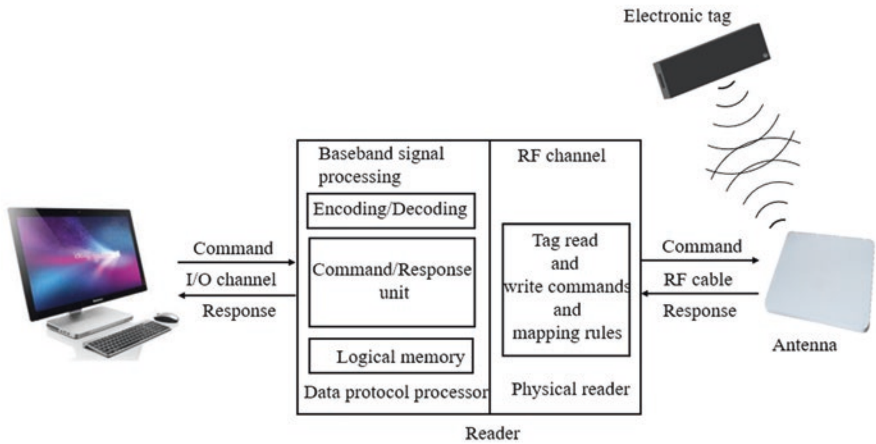

Fig. 13.1 Principles of the RFID system

Read-write distance is a key parameter in RFID systems. At present, long-range RFID systems are quite costly, which is why it is essential to study the long-range reading and writing methods of RFID systems. The factors that affect the read and write distance of the system include the output power of the reader, power consumption of the electronic tag, the receiving sensitivity of the reader, the antenna operating frequency, the Q value of the antenna and the resonant circuit, the coupling degree of the reader and the electronic tag, the antenna direction, the energy obtained from the conversion of electronic tags, and the energy consumed to send product information. The writing distance of most RFID systems is approximately 40–80% lower than the reading distance.

13.2.1.2 RFID Electronic Tag Applications

Identification of Livestock

Recent years saw the continued global outbreak of animal epidemics, causing huge economic losses and seriously endangering people's health and life. To cope with such outbreaks, governments across the globe have begun to attach importance to the prevention, supervision, and control of animal diseases. They have applied radio frequency identification technology to the animal husbandry industry, implemented tracking and identification of animals, and enhanced animal traceability mechanisms. The international standards IS011784 and ISO11785 also stipulate relevant code structures and technical guidelines for animal identification using RFID systems in the production management of livestock. When an animal that wears an electronic tag enters the working area of a fixed reader or when a handheld reader approaches an animal that wears an electronic tag, the reader, whether fixed or handheld, can automatically identify the animal-related information stored in the electronic tag.

There are four common approaches to install the transponder: collar type, ear tag type, injection type, and pill type (Zhao et al. 2012; Wang et al. 2011):

- The collar-type transponder, mainly used in automatic feed distribution system and automatic counting system of milk production, can be recycled among different animals.
- The ear tag transponder (shown in Fig. 13.2) can receive and read related data at a maximum distance of 1 m. Compared with bar code ear tags, it is more suitable for automated breeding processes. As related technologies mature, its cost is going down, giving it the potential to replace barcode ear tags.
- Compared with the above two approaches, the injection transponder is a new comer – its application only begun in the past decade. The principle of the injection transponder is to use special tools to place the transponder under the skin of the animal to be identified. However, this installation method may cause the reader to not read data normally due to the unstable position of the transponder.
- Pill-type transponders, installed in acid-resistant cylindrical ceramic crusts, constitute a highly effective installation method. Once the pill-type transponder is

Fig. 13.2 Individual animal identification with RFID

placed in the fore-gastric page of the ruminant, the transponder will accompany the animal throughout its life to identify its individual information.

Application of RFID in the Field of Agricultural Product Logistics

In recent years, the rapid growth of urban transportation and logistics has made vehicle scheduling and management more difficult. At present, the management of most transportation vehicles also depends on manual recording and transmission. With the increase of vehicles and related business, manual operations will inevitably result in omissions and errors. Meanwhile, the cost of time and the circulation cost of internal information have also continued to increase, and data on transportation cannot be tracked and recorded, leading to increases of operational risks and uncontrollable factors. Moreover, subsequent development and managerial costs have also encountered bottlenecks. Therefore, the operation reform of the urban transportation and logistics is inevitable. As a key technology in the IoT, RFID technology is widely used in intelligent transportation and warehouse logistics management.

As shown in Fig. 13.3, in the process of warehouse cargo turnover and logistics, each piece of cargo and each vehicle is equipped with RFID tags. The basic information of the goods and real-time information of the cargo turnover or logistics process are written into the RFID tags and are associated with the background database. RFID readers ought to be installed at the gates or garage doors that require information registration, so that when the vehicle passes, the RFID reader automatically recognizes, collects, and manages the tag information of the vehicle and goods without manual intervention, improving the efficiency of information transmission and realizing automatic management. The data is transmitted to the background

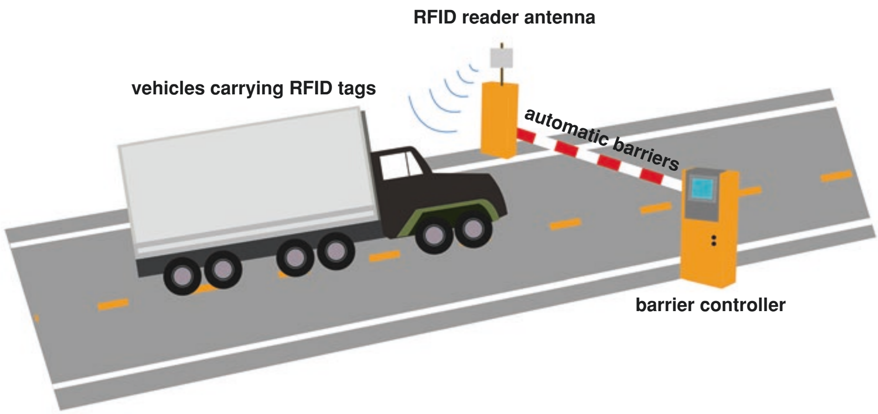

Fig. 13.3 Application of RFID vehicle management system

management platform through the network to verify the legitimacy of the electronic tag information and then process the relevant data information and issue the corresponding instructions. At the same time, a GPRS module must be installed on each vehicle. During transportation, information is transmitted to the background management platform in real time through the GPRS module installed on each vehicle. By adopting such an approach, the transportation process can be better controlled, and the vehicles can be reasonably dispatched.

Application process and principle of RFID electronic tag:

- Vehicle intelligent access management: When a vehicle, equipped with a radio frequency identification tag, passes the gate, the fixed reader automatically communicates with the electronic tag, eliminating manual operations, so that the entry and exit of vehicles could be faster and more efficient. Relevant information such as the entry and exit records are sent to the background management platform by the electronic tag through the network. The combination of the back-office management platform and the vehicle closing gates can determine the legitimacy of vehicles entering and leaving and provide independent, efficient, and uninterrupted storage and logistics data collection and monitoring functions.
- Information processing: In the field of warehouse and logistics information management, the function of radio frequency identification electronic tags is to store information on cargo transportation and logistics. RFID tags are regarded as electronic ID cards of vehicles because of their non-reproducible and unchangeable characteristics and excellent security performance. It is worth mentioning that each RFID tag has a unique ID number. Throughout the entire process, the newly collected data is compared with the original data in the database, the information is managed, the decision-making process is performed, and the corresponding instructions are given to help staff make decisions and find the appropriate vehicles in a manner that is quick and accurate.

- Real-time tracking management: Relying on GPRS technology, information, including whether the vehicle is parked halfway during transportation, why it is parked, and the vehicle's driving trajectory, can be detected. What this means is that the management platform can track and record the state and location of vehicles. Dispatchers stay informed of the conditions of the delivery vehicles through the management platform, allowing them to react instantly to emergency situations.

13.2.2 Bar Code Individual Identification Technology

Bar codes are composed of "bars" and "spaces" of varying widths arranged according to certain rules. Bar code information is transmitted by bars and spaces with varying reflectivity through different widths and positions, and the amount of information depends on the width of the bar code and the accuracy of printing. The wider the bar code, the more bars and spaces are arranged, the greater the amount of information stored in the bar code. The higher the accuracy of bar code printing, the more bars and spaces that can be accommodated in the same width, and the greater the amount of information stored in the bar code. This bar code technology can only store information through the combination of "bars" and "spaces" in one direction, which is why it is called "one-dimensional bar code." For individual identification, a one-dimensional bar code is scanned by a bar code reader to obtain a set of reflected light signals, and then the identified signals are transmitted and processed to obtain the data information stored in the bar code.

There are more than 200 kinds of one-dimensional bar codes in the world with their own unique set of encoding rules. Common one-dimensional bar codes include 39 code, EAN code, UPC code, 128 code, ISBN, ISSN, etc. Since the invention of the UPC code, all sorts of bar code standards and specifications created for different demands have appeared. At present, bar codes have evolved into a vital precondition for commercial automation. Unlike two-dimensional codes, which are mostly used for online goods and Internet information, one-dimensional bar codes remain the dominant form of bar codes used for tangible goods.

13.2.3 Two-Dimensional Code Individual Identification Technology

The two-dimensional code depends on a certain geometric figure to record data symbol in a black and white pattern distributed on a plane surface (in a two-dimensional direction) according to a certain rule. In the coding process, the concept of "0" and "1" bitstreams, which form the internal logic basis of the computer, is used cleverly, and a number of geometrical bodies corresponding to binary are used to represent text numerical information. The technology automatically reads through image input equipment or photoelectric scanning equipment to achieve automatic information processing: on the same unit area, the amount of information stored by two-dimensional codes is nearly a hundred times that of one-dimensional codes. It can store text, pictures, sounds, and other data that can be converted into the digital form. The technology shares some of the common features of bar code technology: each code system has its specific character set; each character occupies a certain width and certain verification functions. At the same time, the technology also features automatic identification of different rows of information and processing graphics rotation changes.

Among the many types of two-dimensional codes, the commonly used codes are: Data Matrix, Maxi Code, Aztec, QR Code, Vericode, PDF417, Ultracode, Code 49, Code 16K, etc. Two-dimensional codes can be divided into stacked/row-type two-dimensional codes and matrix two-dimensional codes. Stacked/row-type two-dimensional codes are built on the basis of one-dimensional codes and are morphologically composed of two or more lines of one-dimensional codes stacked. The matrix two-dimensional code/checkerboard two-dimensional code is composed of a matrix, and the binary "0" and "1" are represented by black and white pixels at corresponding positions in the matrix space. Moreover, the coding is composed of an arrangement of pixels. Some of the commonly used encoding methods include row-type two-dimensional code, Code 49 barcode, Code 16K code, and matrix two-dimensional code.

Two-dimensional codes are widely used in such industries as logistics, agricultural product processing and transportation, security, and traffic management. These are favored due to their unique advantages such as large information storage, low costs, and strong resistance to damage. Meanwhile, owing to the varying characteristics different industries, two-dimensional codes are used in different workflows in different industries. At present, the application of two-dimensional codes in tracing agricultural products is mainly agricultural product processing and logistics. The process is as follows. First, with respect to the entry and verification of raw material information, the supplier of agricultural products enters the raw material production data (origin, production date, shelf life, etc.) into a two-dimensional code and provides the product with the two-dimensional code tag to the buyer. Second, in terms of the entry and verification of production recipe information, one enters the production recipe information (raw material name, weight, ratio, etc.) into a two-dimensional bar code, prints the two-dimensional code tag, and pastes it on the raw material. Third, concerning the entry and query of finished product information, in each inspection process following the input of raw materials, the inspection data is entered using a data collector. At last, the data recorded in the data collector is uploaded to computers to generate the original production data, and this database is used to publish the raw material information of the product on the Internet (Zhou et al. 2012; Fang et al. 2012).

13.2.4 Comparison of Two-Dimensional Code and RFID

In recent years, two-dimensional code and RFID technology have emerged as the most widely used tag technologies in the world. It is foreseeable that almost all items in the future will come with a unique two-dimensional code or RFID tag. It is safe to say that tags are the most basic tools for information storage and transmission in IoT, and the telecommunication applications based on the tag technology will be the mainstream application in IoT. Therefore, telecommunications operators must actively promote the migration of label applications to telecommunications networks.

Since its advent in 2004, two-dimensional code has been favored by telecommunications operators in a number of countries for its large data storage, fast and convenient transmission, and strong resistance to damage. Two-dimensional code has achieved universal application worldwide and has become a typical success story of “mobile + tags.” Two-dimensional code is extremely convenient for both storing and reading information. On the one hand, the information storage capacity of two-dimensional code is tens to hundreds of times that of the one-dimensional code. Therefore, all the information of a given item can be stored in one two-dimensional code. To view related information, one only needs to scan the code with a reading device without having to establish a database in advance. On the other hand, users only need to install the reading software for free to acquire information through simple code scanning operation. Two-dimensional code is primarily transmitted through packaging, newspapers, books, magazines, products, advertisements, and personal business cards. The major cost of its dissemination is printing fees that do not cost much. Thus, the biggest advantage of two-dimensional codes, like one-dimensional codes, is the ultralow cost.

As a wireless version of the two-dimensional code, RFID represents the future of tag technology. It is considered one of the most promising information technologies in the twenty-first century. RFID, a noncontact writing and reading technology of data, uses radio frequency signals to identify target objects and obtain related data information. Compared with two-dimensional codes, RFID features more advantages.

First of all, RFID is waterproof and antimagnetic. It also features high temperature resistance, long service life, and long reading distance, which means that RFID can work in harsh environments, freeing it from all geographical restrictions. These features are not available in two-dimensional codes and barcodes.

Secondly, RFID makes information identification more intelligent. It allows multiple readings and writings of information. Furthermore, RFID encrypts the single product information stored in the tag and is equipped with larger storage capacity. The RFID tag can store data ranging from 512 bytes to 4M bytes, allowing all items in the world to obtain a unique “identity” like the case in IPv6. At the same time, RFID can record production, transportation, storage, and other related information and identify the machines, animals, and individuals.

Finally, the RFID identification does not require manual intervention, which reduces labor costs. Its operation is convenient and fast, and it can identify objects that are moving at high speed and read multiple tags in batch. Based on these unique advantages, RFID can be extensively adopted in asset management, tracking, logistics, production, transportation, anti-counterfeiting, and any field that demands the collection and processing of information. It can provide information relating to production, transportation, and storage and can identify machines, animals, and individuals. It is safe to draw the conclusion that RFID will serve as the most basic information tool in future IoT.

13.3 Agricultural Products Traceability System

13.3.1 The Overall Framework

Food safety relates to public health and safety. The traceability of agricultural products can establish an information database covering all processing stages of agricultural products, ranging from the initial stage to more sophisticated stages. The agricultural product traceability code is the transfer carrier of information, the agricultural product traceability tag is the tangible link of the system, and the agricultural product traceability information management system is used to provide services. Throughout the entire cycle of production, testing, and circulation of agricultural products, the system provides safe production services for producers through the electronic management of production files and offers traceability services to consumers through the information-based detection and circulation of pesticide residue. Additionally, the system also builds platforms for data integration, query, analysis, and early warning for the supervision by the trading center. Consumers can check the relevant food information at any time to ensure food safety. The system creates a smart agriculture to ensure the safety and credibility of agricultural products and establishes a traceability information database for production and circulation. Apart from this, it also conducts full-process monitoring and management of each link, carries out comprehensive analysis and utilization of traceability information, and provides a platform for information traceability. In addition, comprehensive information services are provided through such channels as the Internet and clients. The traceability system is characterized by early warning of safety, traceability at source, traceability of flow direction, information inquiry, determination of accountability, and the ability to retrieve products.

A flowchart of the traceability of agricultural products is shown in Fig. 13.4. During the production and harvesting stage, agricultural products are assigned with batch numbers through traceability information and then enter storage and circulation, which is called entering the market. After entering the market, the relevant node data is entered into the agricultural product circulation supervision system, and the circulation traceability information is written on the basis of the original

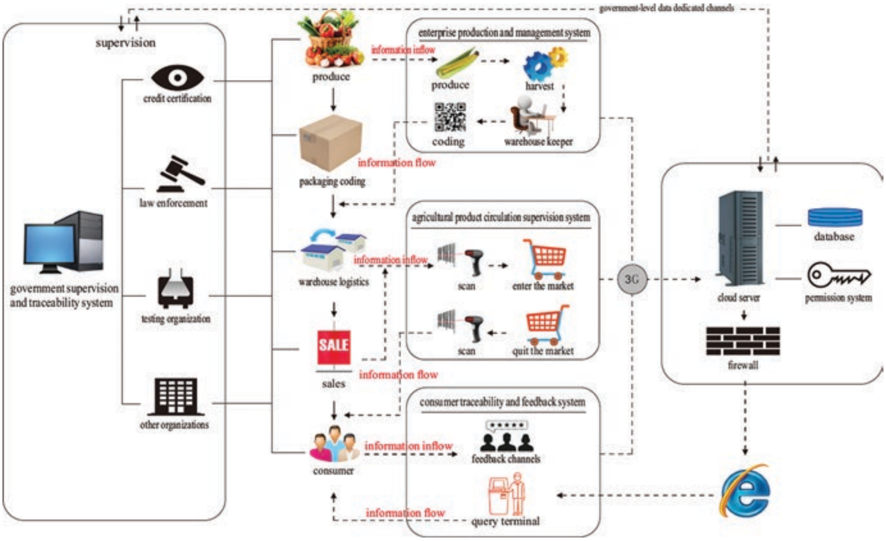

Fig. 13.4 Agricultural products traceability flowchart

production information. After sales, the products reach the consumers and exit the market. At this time, consumers can scan the two-dimensional code to acquire the source information. They may also voice their feedback and complaints according to consumer experience. The government and inspection department could tap into the data with the traceable cloud server through a dedicated data channel, hence achieving transparent supervision of the entire process of agricultural products from the field to the dining table.

The traceability system should be led and managed by the government to transparently supervise the production and distribution nodes of agricultural products. In addition, third-party organizations, such as quality inspection agencies, ought to conduct random sampling inspections of agricultural products at various nodes, and industry associations must supervise agricultural production enterprises. At the same time, consumers voice their feedback and complaints about products. All this information will be incorporated into the corporate credit system to keep consumers informed and to protect their legitimate rights and interests.

Different business entities can manage and acquire the source tracing information according to the principle of rights distribution. For example, consumers can only acquire the specified basic source tracing information and cannot acquire technical and confidential information such as the company's production process. The government, on the other hand, has certain authority to supervise the information of enterprise production process nodes.

The agricultural product traceability information database mainly includes information on production, purchase and transaction, processing, logistics, retail, and traceability websites.

13.3.2 Agricultural Product Traceability Information Management

13.3.2.1 Production Information Management

During planting, information, such as seed and fertilizer purchase, sowing, irrigation, fertilization, picking, and testing, are collected and monitored according to different batch numbers, thus facilitating the traceability management of planting information. Meanwhile, IoT technology in agriculture is adopted to build smart agriculture and to obtain information about plant growth environment, such as temperature, humidity, light intensity, plant nutrient content, and other parameters. Such adoption enables the acquisition, management, display, and analysis of information of all base test points and achieves automatic control and management of operations.

During the processes involved in livestock farming, relevant data that must be recorded include the source of livestock (cattle, sheep, etc.) seedlings, information on commercial livestock (cattle, sheep, etc.), immunization, diagnosis and treatment, purchase and use of veterinary drugs, purchase and use of feed or additives, disinfection, death treatment, monthly production report, operator, etc. It is critical to formulate a corresponding system and strictly follow the specifications for production, and each base must be connected to the Internet or home broadband (for video surveillance). Online environmental monitoring and management systems can be installed in farms, and sensing equipment can be relied on to monitor the temperature, humidity, and air quality in livestock (cattle, sheep, etc.) farms and to give early warnings.

The importance of environment and water quality monitoring in aquaculture is self-evident. The production process is highly demanding with respect to a number of factors that include water quality, dissolved oxygen, water temperature, feed, climate, light, and biology. Effective monitoring and recording of these factors are essential to traceability of aquatic product quality. Using automatic detection and control technology, technicians can achieve accurate online monitoring of changes in water quality values, dissolved oxygen, water temperature, and water depth through various sensors.

13.3.2.2 Purchase and Transaction Information Management

The IoT system for the purchase and transaction of agricultural products aims to achieve data collection and product quality control management in the procurement process using modern information technologies such as RFID, RFID read-write equipment, Internet, wireless communication networks, 3G, IPV6, and intelligent control. It is the initial link of the information management for the entire chain of agricultural product logistics.

Production of Electronic Tags and Data Upload
Electronic tags of the products produced by the production base (the products purchased by the purchasing department) made before the products are packed, and the related product information is transmitted to the database of the system server through the network via handheld RFID card readers or intelligent mobile read-write devices. This marks the start of the whole process of circulation management and tracking. The related product information mainly includes the product name, origin, quantity, size of the warehouse, estimated arrival time, etc. Processing operations are then carried out on the data server of the IoT, so that preparation and coordination of the cold storage for the distribution headquarters can be effectively managed.

Management of Purchase Orders
Purchase orders are generated mainly relying on inventory information and customer orders, and management of purchase orders is achieved. Such functions are enabled by RFID, RFID read-write equipment, mobile RFID read-write equipment, wireless communication network, Internet network, computer, etc.

13.3.2.3 Processing and Warehouse Logistics Information Management

From the arrival of agricultural products to the factory and to inspection and processing, the entire process is tracked, and related information is collected according to each batch number. Each processed product will be assigned a two-dimensional code for the corresponding batch number and an RFID agricultural product identification mark. During the processing of agricultural products, the perception layer mainly works through two-dimensional codes, acquisition of RFID agricultural product identification information, and processing environment monitoring.

Concerning market circulation, real-time monitoring of environmental information during warehousing and logistics can avoid quality disputes after the products are sold (Fig. 13.5). This IoT system can quickly locate the node information where quality problems occur. While protecting the interests of businesses, the system can also issue prompt warnings of quality and safety information. In terms of product identification and traceability in agricultural product logistics, RFID technology and barcode automatic identification technology are often used, whereas in transportation positioning and tracking, GPS positioning technology, RFID technology, and onboard video recognition technology are frequently used. Additionally, regarding quality control and status perception, sensor technology (temperature, humidity, etc.), RFID technology, and GPS technology are favored.

Perception Layer of Agricultural Product Logistics IoT
The perception layer mainly includes sensor technology, RFID (radio frequency identification) technology, two-dimensional code technology, multimedia (video, image acquisition, audio, text) technology, etc. The perception layer, mainly used to identify objects and collect information, bears similarities with the role of skin and facial features of man. In the circulation of agricultural products, it identifies and

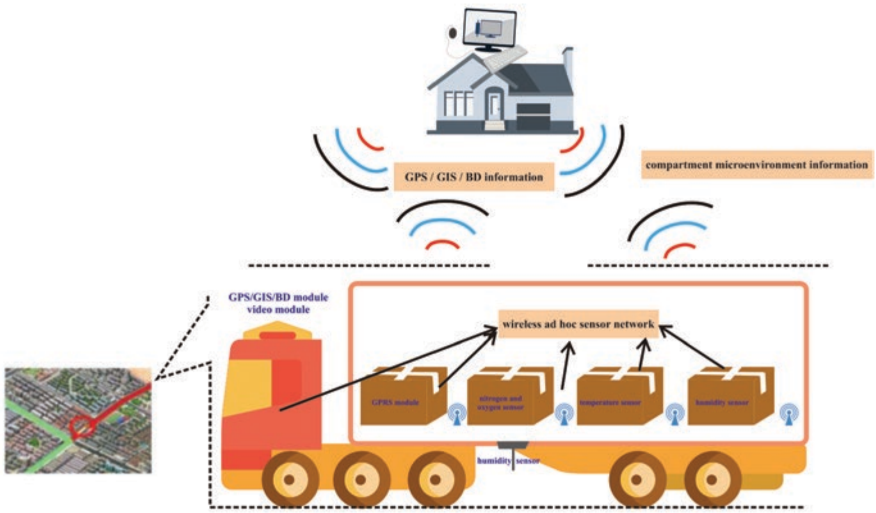

Fig. 13.5 Logistics environment monitoring

collects the relevant information of agricultural products during the entire circulation.

Transport Layer of Agricultural Product Logistics IoT

The network layer includes a converged network of communications and the Internet, a network governance center, an information center, and an intelligent processing center. The network layer, transmitting and processing the information obtained by the perception layer, is similar to the nerve center and brain of man. The information system for agricultural product logistics management and operation in certain areas tends to rely on the company's internal LAN technology and interfaces with the Internet and wireless networks. In places where wiring is not convenient, wireless local area networks are often used. The combination of Internet technology and GPS technology is often adopted in large-scale agricultural product logistics transportation management and dispatching information systems. In the logistics center information system with storage as the core, network technologies, such as fieldbus technology, wireless local area network technology, and local area network technology, are relied on, while in network communication, wireless mobile 356 communication technology, 3G technology, and M2M technology are the major components.

Application Layer of Agricultural Product Logistics IoT

The application layer is the deep integration of the IoT technology and industry expertise. Through the combination of the IoT technology and the industry needs to achieve the industry intelligence. The application layer is charged with three tasks: one, carrying out cloud-based processing, such as the acquisition and storage of information for agricultural products circulation IoT; two, providing IoT cloud services in the purchasing, allocation, and transportation; and three, offering cloud services on circulation information. The application layer constructs agricultural product logistics information cloud processing system, electronic transaction information cloud service system, distribution information cloud service system, transportation information cloud service system, and agricultural product circulation information service system. Additionally, it develops and integrates the cloud computing resources of the agricultural product logistics IoT and establishes the agricultural product logistics IoT cloud computing environment and application technology system. Cloud computing capabilities, storage space, data knowledge, model resources, application platforms, and software services are provided at the application layer. Moreover, the application layer works to improve the collection, management, sharing, and analysis of agricultural product logistics information. It brings together different factors of agricultural product circulation and allows different pieces of information to converge. Relying on the application layer, the rapid formation and expansion of the industry chain of agricultural product logistics could be achieved.

13.4 Application of Production Traceability Using IoT Technology

13.4.1 Traceability of Crop Production Information

13.4.1.1 Crop Farming Traceability System

The traceability of crop farming covers the production, circulation, and marketing of crops. Figure 13.6 illustrates a functional structure of IoT-based crop production traceability. There are two functional modules in production, including the agricultural product production records management module and the agricultural product environmental information detection module. The former can achieve the record management of fertilizer and water operations, plant protection operations, and other agricultural operations in the agricultural product production process. The latter, through different sensors, enables the automatic collection of such data as air temperature and humidity, carbon dioxide concentration and soil moisture, fertility, and heavy metal content. In circulation, real-time monitoring of environmental information during warehousing and logistics processes is used to forestall quality disputes. Through monitoring, quality-related problems will be identified as soon as possible. While protecting the interests of businesses, the system can also issue early warnings of quality and safety information. After agricultural products enter circulation, the comprehensive management of licenses, operating records, and purchase and sales vouchers of each node effectively eliminates the blind spots on the circulation chain. After the products enter the market, consumers can trace the source relying on the two-dimensional code, batch number, query code, and so on.

The traceability system, centered on the field production records, achieves comprehensive management of agricultural production processes, including the names

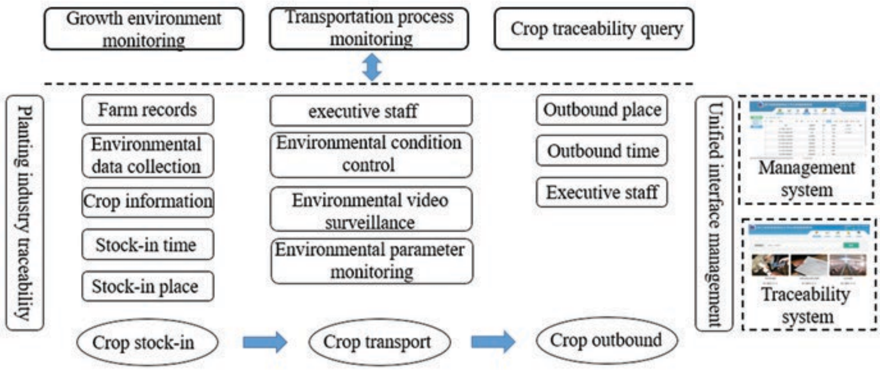

Fig. 13.6 Functional structure of IoT-based crop production traceability

of agricultural inputs, fertilizing, spraying, detecting, and harvesting operations. The farming information records include the following aspects:

- Fertilizer and water operation information record, including fertilizer types, ingredients, fertilization time, manufacturer information, the duration and frequency of irrigation, area water consumption, etc.
- Plant protection operation information record, including spraying time, pesticide types, object of prevention, spraying frequency, pesticide dosage, etc.
- Farm operation and management information record, including crop variety, cultivation region, harvesting, and other operation information

The system can also collect the growth environment parameters (including weather, altitude, soil fertility, and other information) in real time via IoT networks at different stages of agricultural product production and draw historical curve charts for query. Environmental data collection mainly includes the following aspects:

- General parameters are collected by various sensors, including air temperature and humidity, soil temperature and humidity, illumination intensity, carbon dioxide, ammonia nitrogen, etc.
- Meteorological parameters are collected by meteorological stations, including air pressure, temperature, humidity, wind speed, precipitation, etc.
- Soil information is collected by detection equipment, including soil fertility, heavy metals, soil structure, etc.

Real-time monitoring and early warning of the environment during the warehousing and transportation of agricultural products can minimize the loss and quality problems caused by the storage and logistics environment and are conducive to the monitoring of product quality. System functions include:

- Warehousing and logistics environment monitoring: general parameters, including cabin temperature and humidity, are measured by sensors; video surveillance is achieved using an infrared dome camera; and position information is obtained by the GPS module.

- Basic function parameters, including basic information of warehousing and logistics, acceptance handover management, and report form management.

When the agricultural products enter circulation, if only the producers and consumers are involved, the difficulty of tracing is relatively low, but in fact, after the agricultural products leave the production base, there are a large number of circulation points, and the supervision is quite challenging. Therefore, a circulation information monitoring module is needed to comprehensively monitor and manage the channels, routes, and nodes that agricultural products pass through from production to consumption, thus eliminating the blind spots in circulation. The comprehensive management of each node includes the operator's archives, product quality control (variety, quality inspection, and so on), purchase certificate, records and sales vouchers, and other types of information.

When agricultural products are purchased, consumers can trace the source using the two-dimensional code, batch number, query code, etc. The query channels mainly include Internet portal (Web), query machine (Web), mobile bar code access (Web), short message service (SMS), interactive voice response (IVR), and other methods (such as WeChat, Yixin). The content of the query primarily covers information on origin, production, quality inspection, logistics and storage, quality standards, etc. (Fig. 13.7).

Fig. 13.7 Traceability query results page

13.4.1.2 Application of Farming Product Traceability System

Liu et al. (2014) constructed a RFID-based vegetable safety traceability system based on the actual management scenarios of the inspection department. The system includes business framework module, technical framework module, and safety guarantee system module. Furthermore, it also covers the functional demands of vegetable planting bases, vegetable processing factories, and vegetable import and export ports and sales points, and interface standards are formulated for the traceability system. The results of operation demonstrated that the traceability system is reliable and effective. The focus on food safety problems in fruit and vegetable planting and processing is concentrated on the detection of pesticide residues. This approach can achieve monitoring, yet it fails to eliminate the hidden dangers from the source. The application of RFID technology has fulfilled this demand, and the food safety control of fruits and vegetables will further improve with the support of relevant regulations.

Shen (2017) made thorough use of network technologies, such as RFID, to build a cold chain logistics traceability system for fruits and vegetables. The system was distributed and managed in the form of subsystems, including subsystems of fruit and vegetable production, wholesale, logistics, sales, supervision, inspection, and retrospective inquiry. Each subsystem had a corresponding information database, and the functions of the subsystem also work independently. The system relies on codes to identify all processes relating to fruits and vegetables from the place of production to consumption, thus making the traceability information complete.

Based on RFID technology, Jiang (2017) established a tea quality and safety traceability system. The first working process of the system is to place RFID tags in the tea farms for collecting and recording information on fertilization, pest severity, pesticide, spraying time, climate conditions, and so on and then upload the information to the information processing center of traceability system. The second process is the processing of fresh leaves after picking, and the collected information include the source of the tea, the name of the company that processed the fresh leaves, and the main technical parameters of processing. The third process relates to packaging and finished products. In addition to collecting general packaging information, a close relationship is established between the RFID tag of the finished products and the RFID tag of the tea farms to facilitate traceability by consumers. The fourth process covers all the relevant information and data on the storage, logistics, and sales of tea products. Due to the unique characteristic of RFID tag, one only needs to bind the ID number to the data of the circulation processes of tea to achieve traceability.

13.4.2 Livestock Farming

Livestock farming, a typical process-based manufacturing industry, is characterized by the fact that the products, once produced, cannot be reversed. The safety management of products in livestock farming may encounter problems in all processes, including production, processing, storage, transportation, and sales. In recent years, food safety incidents have repeatedly occurred, causing panics among the general public. Therefore, information-based product safety has become a key part of food safety supervision. Using information technology to improve the quality and safety of animal products and production has emerged as a major issue for the government, academia, and the public.

13.4.2.1 Quality and Safety Traceability System for Products in Livestock Farming

The goal of this traceability system is to achieve the supervision of product information along the entire production chain, from breeding to market sale, and to realize accurate inquiry of products. The processes mainly include breeding, quarantine, verification and inspection, the period before slaughtered, slaughtering, sales, slaughterhouse to market, and backtracking.

Architecture Design of the Traceability System (Fig. 13.8)

Process Design of the Traceability System

During the whole process of meat production, processing, warehousing, and logistics, RFID tags are first used to identify the relevant information of the primary processed products (Fig. 13.9). At this time, the individual production information of the products is stored in the database, with the RIFD as the identification number. During the processing process, two-dimensional codes are used to identify processed products. Taking pork as an example, during the production process, RFID tags are used for individual identification and marking of pigs, and feeding information, health status, and growing environment information are all recorded and stored in the ID number identified by RFID. During processing, a pig will be processed into several packages of pork products. Meanwhile, two-dimensional codes containing pork-related information are printed on the pork packaging boxes, i.e., each package is identified and tracked in the form of a two-dimensional code. The relationship between the two-dimensional code and RFID is many-to-one, associating production with processing. During transportation, the two-dimensional code will store and track the information of each product until the pork is sold to the consumer. Consumers can scan the two-dimensional code through mobile phones and smart terminals to get access to the information of the corresponding pork products from the network.

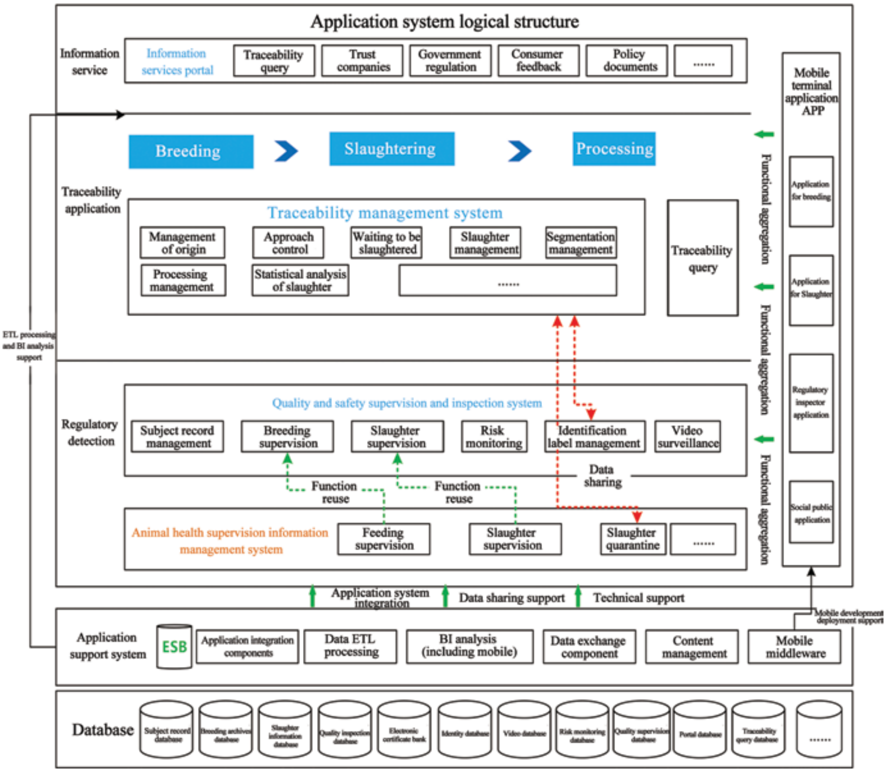

Fig. 13.8 Overall architecture of the traceability system

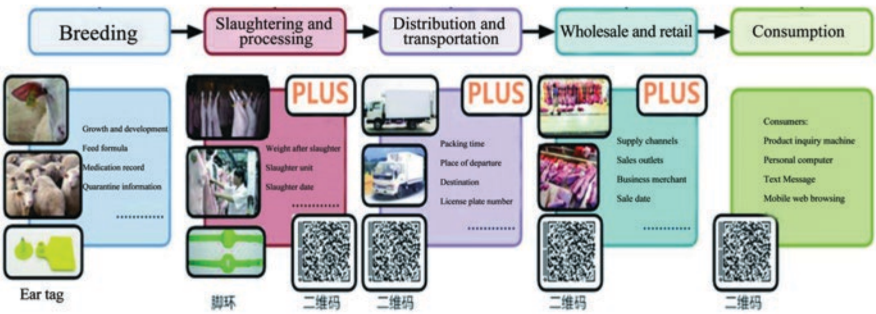

Fig. 13.9 The information flow and traceability process

13.4.2.2 Traceability Application of Products in Livestock Farming

In October 2010, the Ministry of Commerce of China announced the pilot project to construct traceability system of meat and vegetables in large- and medium-sized cities nationwide. Chengdu was one of the first ten pilot cities. At present, Chengdu's meat and vegetable circulation traceability system covers more than 10,000 points of sale. Let us take the pork traceability system as an example; citizens can trace detailed information via the system, covering wholesalers, slaughtering companies, slaughtering time, meat inspections, animal inspections, pig suppliers, origin of pigs, origin quarantine number, and license plate numbers of transport vehicles.

RFID technology in IoT is widely used as it is simple and practical, and as such, it can quickly respond to food safety management, trace the source, determine problems, and enable effectively control. Song (2014) designed a pork safety traceability management system based on RFID and used RFID tags as the main way to collect information, while taking into consideration the actual production environment of pork. The results demonstrated that through sensing and RFID technology, the production process of pork can be accurately tracked, and the goal of safe and accurate traceability of pork can be achieved. Zhang (2017) combined RFID and NFC technology to collect information in the process of lamb slaughtering and processing and mainly collected information on seven key nodes of this process to achieve traceability of lamb quality and safety in Xinjiang.

13.4.3 Aquaculture Industry

China is a major country in the production, export, and consumption of aquatic products. As the proportion of aquatic products consumption in food consumption gradually increases, the quality and safety of aquatic products have entered into the spotlight. At present, the foundation of China's aquatic product quality and safety remains weak compared to developed countries, and the key issues affecting the quality and safety of aquatic products have not been addressed. Therefore, there are still many hidden dangers to the quality, sanitation, and safety of aquatic product, and the quality and safety issues of aquatic products remain salient. Such problems as excessive hygiene standards, excessive or illegal use of additives, irregular packaging of aquatic products, fraudulent labels used to deceive customers, adulteration, shoddy products, and artificial water injection have not been restricted. Quality and safety issues of aquatic products exert a negative impact on public health, social stability, and China's international image and cause severe economic losses. Therefore, strengthening the quality and safety management of aquatic products is the key to ensuring the sustainable development of aquaculture. In particular, production records, the traceability of product flow, and the traceability of product quality ought to be made available to the general public.

13.4.3.1 Aquaculture Safety Traceability System

Figure 13.10 illustrates the information flow in the aquaculture traceability system. The aquaculture safety traceability system first relies on both automatic information collection and manual collection to record information into the database as the

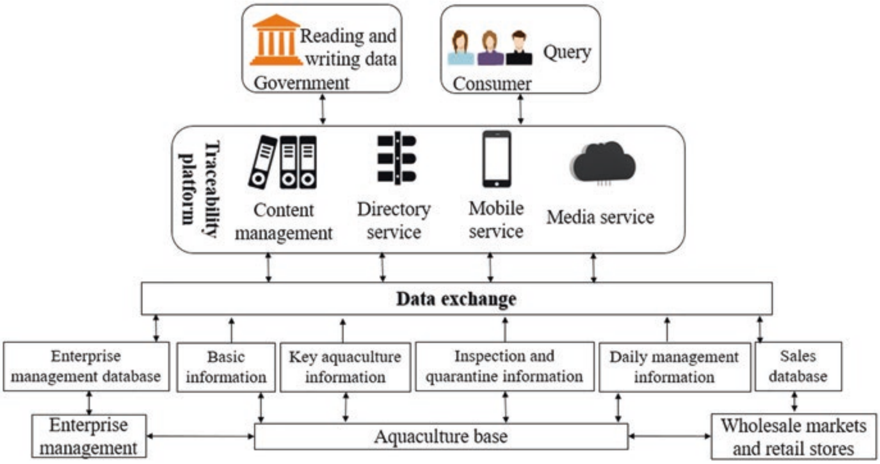

Fig. 13.10 IoT-based aquaculture safety traceability information flow

original data for quality traceability. The key of quality and safety control in aquaculture is that the information collected ought to be factors that are closely related to the safety of aquatic products, including basic information, key aquaculture information, inspection and quarantine information, and daily management information.

Basic information is the static information used to describe the basic attributes of aquatic products, including aquatic product types, origin, name, and meteorological information of the origin.

Key information in the breeding process mainly includes information on seedling, feed, drug, and water quality. The seedling information includes basic information, drug residue information (pesticides, veterinary drugs), and information on heavy metals, microbial indicators, and virus; feed information includes basic feed information, storage information, and use information; drug information includes basic information, storage information, and usage information; and water quality information includes routine, microbiological, and heavy metal information (Zhang 2016).

With respect to the inspection and quarantine information, the detection of aquatic products is a key to ensuring the safety and quality of aquatic products. This process includes detection along the aquatic product supply chain, covering the seedlings, breeding, delivery, sales, and so on, and the information so acquired are then sent to the database. The detection includes water quality detection and drug residue detection.

Daily management information. In aquaculture, a number needs to be configured for each breeding cage as the unique identification certificate for the two-dimensional code. The daily management and the feed and drug are recorded with the two-dimensional code label, the carrier, the breeding cage, and the unit. At the same time, each bag of feed and drug adopts a two-dimensional code label as a unique

Table 13.1 Classification of traceability information

Category	Data content	Data source	Update frequency	Openness
Basic information	Types of aquatic products, origin, name, meteorological information (temperature, precipitation, wind speed, etc.)	Production enterprises, meteorological departments	Fixed-point monitoring, real-time update	Open to the public
Key information in the process	Seedling, feed, medicine, water quality, culture pond	Production enterprises	Real-time update	Open to the public
Inspection and quarantine information	Seedling, aquaculture, factory and sales	Inspection and quarantine department	Real-time update	Inter-departmental opening
Daily management information	Remote pond management, feed and drug use	Production enterprises	Real-time update	Inter-departmental opening

identity, which records purchase information and usage information. Table 13.1 is an illustration of the classification of specific traceability information.

The general supply chain of aquatic products is farms → aquatic products enterprises → aquatic products wholesaler → aquatic product retailer → consumers. The traceability system ensures the accuracy of the information of aquatic products in all processes along the logistics chain. Figure 13.11 offers an illustration of the complete traceability system of aquatic products. Horizontally, it consists of the supervisory and traceability system, production management system, transaction management system, and traceability information query system. Vertically, it consists of the supervisory body, responsible body, information transmission, and product circulation.

The regulatory bodies, including national regulatory platforms and local regulatory platforms, are responsible for the formulation of some rules. They are also charged with the task of publishing product information to consumers and receiving consumer complaints and feedback. The responsibility body means that the enterprise is responsible for the aquatic products cultured and purchased. Wholesalers must purchase products legally using the legal identity of the enterprise, and at the same time, the farmers' market must ensure that only valid aquatic products can enter into the market according to the effective barcode printed by the enterprise. Aquatic products and related information are distributed alongside two-dimensional codes and receipts, ensuring the safe flow of products. The traceability labels of product quality and safety clearly record the product name, batch number, transaction date and quantity, aquatic product company name, and traceability number, and the ciphertext records each breeding indicator. Once a safety accident occurs, the cause of the accident can be accurately identified.

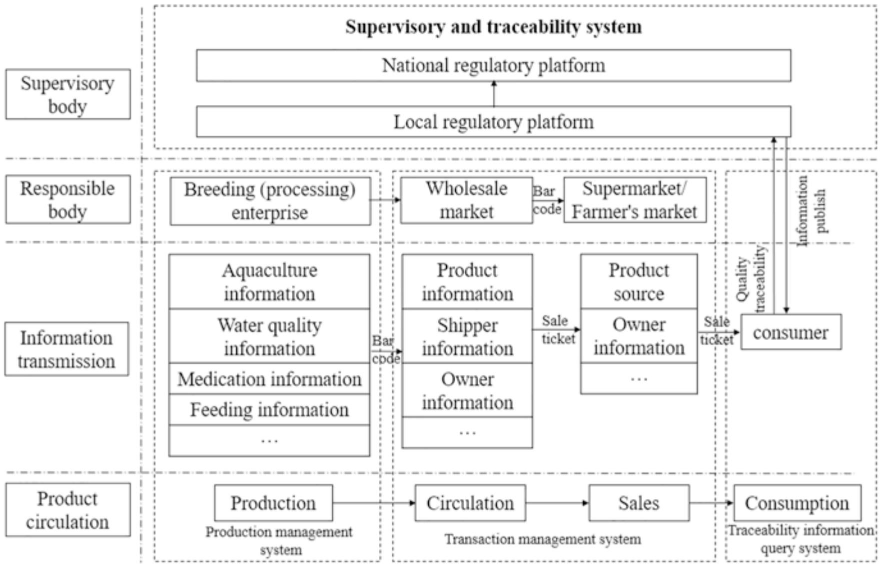

Fig. 13.11 Aquatic product traceability IoT system framework

13.4.3.2 Application Examples of Aquatic Traceability

As a major aquaculture province, Jiangsu has set up retrospective supervision subcenters in more than ten aquaculture departments in the province. The province established a three-level management system of "provincial center to subcenter to traceability point" and a variety of aquatic product quality traceability models. A four-in-one framework for the aquatic product quality and safety traceability has been established, including "aquatic product quality and safety traceability, online monitoring of water quality, remote diagnosis and treatment of aquatic animal diseases, and aquaculture environmental supervision." Using digital barcode and two-dimensional code technology, digital connection of water quality management, farmers, production place, feeding, medication, and other information in the aquaculture production process is achieved (Huang and Wu 2014). Jiangsu Province has initially achieved traceability of the source and destination of aquatic products, and accountability for safety issues can be investigated.

In relation to the short-range object recognition technology, Yan et al. (2013), taking tilapia as the research object, designed and developed a type of IoT based on radio frequency identification and product electronic code, including five subsystems: breeding management system, processing management system, distribution management system, sales management system, and inquiry supervision system. Zhang (2016) designed an aquaculture safety traceability system based on multi-information fusion. The system provides reference data for aquaculture health through fusion and analysis of multisource information. Regarding the complex tracing problems caused by aquatic products in ponds, a tracing algorithm based on two-dimensional codes is proposed – tapping into the idea of collection and recursion to connect aquatic information flow and to ensure the integrity of tracing information.

13.5 Summary

Problems of agricultural products in any process, from production to sale, may cause food safety problems. Traceability systems of agricultural products can monitor the information of the whole production process, providing an effective way for food safety management. This chapter laid an introduction of the application of the IoT technology in traceability systems of agricultural products, covering the key technology, system structure, and specific applications. It is demonstrated that the development of the IoT technology drives food safety forward. In particular, it is shown that the development of information sensing technology makes the information collection more comprehensive. There is still a trust crisis in the current food traceability system, and the best solution is to make use of blockchain technologies to integrate the data of key links in agricultural production, circulation, and sales, thus bringing about a seamless convergence between blockchain technology and IoT technology. In agricultural production of the future, all products will have their own identities, and the agricultural IoT technology will penetrate into all aspects of agriculture. Through the network, people are able to acquire various information on the production, processing, and logistics of agricultural products.

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Chapter 14
Integrated IoT Applications Platform Based on Cloud Technology and Big Data

Pengcheng Nie, Na Wu, Yong He, and Zhuoyi Chen

Abstract One key symbol of modern agriculture is information-based operation, which constitutes an important means for securing agricultural development and prosperity in rural areas. Modern agriculture is essential to agricultural production and management, agricultural industrialization, and the improvement of agricultural facilities and equipment. Thanks to extensive research, recent years saw breakthroughs in the theories of big data, cloud computing, and IoT, and as a result, a number of applications have sprung up, such as application of research on big data and cloud computing in forestry, application of research on big data and IoT in aquaculture, and application of research on IoT and cloud computing in agriculture. The application of these new technologies has brought tangible benefits to local industries and positive social ramifications.

Keywords Cloud computing · Cloud services · Remote management system · Big data · Traceability system

14.1 Introduction

Big data refers to the mega-sized, fast-growing, complex, and changing data sets that cannot be captured by conventional search engines within a certain period of time, and that can only be mined using new search methods. At present, it is generally accepted that big data should have 5V characteristics, namely, volume, velocity, value, veracity, and variety. Agricultural big data resources have become increasingly prominent, and its foundation has been laid by massive multisource data. In this field, researchers tend to focus on monitoring and early warning, data mining, and information-based services in agriculture. Agricultural data features large volume, complex structure, strong real-time performance, and real-time variances.

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Therefore, obtaining effective information from massive sets of data in agriculture through big data technology is a crucial way to solve the problem of high-dimensional strong coupling of agricultural variables.

Cloud computing is an internet-based approach that is used to provide high-quality and fast services. The idea is to combine corporate computers with memory chips, apply computing algorithms, search relevant databases, and eventually locate data, allowing one to get access to data at extremely high computing speeds. The obtained data can be analyzed by algorithms, and finally the relevant trends can be acquired. The IoT cloud platform, relying on cloud computing technology, analyzes and processes the obtained data in real time and provides decision feedback, so that satisfactory growth environment is ensured. Thus, real-time monitoring and regulation of agricultural production are available with the platform. Cloud computing can also be applied to the logistics and traceability of agricultural products, thus achieving entire-process management that covers production, processing, logistics, and sales. The combination of agricultural IoT and cloud computing gives birth to information-based and software-centered production models that achieve precise control of the entire process of production and enable refined management of modern agriculture.

14.2 Construction of IoT Platform in Cloud

14.2.1 Elements of Cloud-Based IoT Platform

From the perspective of agricultural services, the intelligent applications for supervision and production are centralized for unified display and dispatch, and the information system of all bases, including those dedicated for crop farming, aquaculture, and livestock farming, is uniformly displayed in the exhibition center, allowing us to observe the actual production conditions in those bases. Moreover, management and operation of the system can be carried out in an independent manner (Xu et al. 2014).

Agriculture, as the primary industry, is of great significance for the survival and development of a nation. An intelligent display center can be built to provide effective services and guidance to local farmers for production. More specifically, IoT sensing technology can be used to guide production, and video monitoring technology can be adopted to provide farmers with training and support of production management, helping them increase yield. Furthermore, farmers can rely on the Internet to build marketing networks and tap into remote education to improve their income. Additionally, the aggregated data acquired via the monitoring of production can be used to provide expert guidance on the control of pests and diseases in crop farming. The creation of such a center enhances services that improve production and provides guidance for building information-based agriculture.

14.2.1.1 Display and Management of Production Sites

The IoT cloud platform shows the summarized information of each production site in the form of brief graphics, including location, profile, geologic plan, building plan, video, data curve, related statistics, etc.

Videos relating to professional knowledge, corporate success stories, and Internet-based marketing of products in crop farming, aquaculture, and livestock farming are collected from government departments, colleges and universities, and the Internet and are provided on the platform.

Relying on the platform, producers are able to conduct production under the guidance of experts by making reference to the agriculture-related technologies that already have been made public and various databases.

The platform also supports the real-time management of production sites. More specifically, users have access to the module, operation, and other processes of production sites, and when abnormal operation is detected, the administrator can immediately end the operation and force the user to exit (Calheiros et al. 2011; Liu 2019).

14.2.1.2 Expert System and Expert Remote Consultation

The platform provides an expert system where experts and farmers can conduct two-way communication. For instance, remote diagnosis services for the control of pests would be available.

An expert bank is set up to provide guidance relating to classification for multiple industries, including vegetable stem cultivation, livestock farming, aquaculture, fruit cultivation, flower and wood planting, etc.

Such real-time remote technical consultation means that experts and farmers can communicate online through the network. According to the collected data of each production site, via comprehensive analysis and the remote video monitoring system, experts can advise on production, control of diseases and pests, and other related operations. The specific functions of the platform in this regard are as follows:

- Real-time remote technical consultation: farmers are provided with real-time technical consultation, and experts and farmers can communicate face to face via the Internet.
- Remote diagnosis of diseases and pests: including the sharing of images, files, and other materials that ensure the accuracy of such diagnosis. Farmers can send physical samples of the diseases and pests to experts through the platform, and experts can give diagnosis according to the actual symptoms.
- Remote monitoring of epidemics: Cameras can be installed at production sites, so that experts can check the situation at any time through remote visits and give technical guidance in a timely and convenient way.

14.2.1.3 Statistical Analysis

The production analysis and decision-making are provided by the platform based on data stored on production and environment, and managers can tap into such functions according to their requirements. It is noteworthy that analysis charts can be customized as needed. The module responsible for production analysis and decision-making mainly contains the following functions:

- Regional statistics. The module collects and sums up the basic information of the same type of production sites, including the floor space, annual output, sales volume, and number of staff, so that future total output of the same type of production sites can be estimated.
- Data storage, statistics, and management, meaning to store, count, and manage the information imported by the sensor and detector automatically, as well as to store and maintain production data, which can be used by the monitoring and tracing system at the same time.
- Statistical analysis of data: statistical analysis of various data in the production area is conducted, and reports are delivered to managers for decision-making.

14.2.2 Network Environment Design

14.2.2.1 Network Resource Pool and Load Balancing Design

Figure 14.1 is an illustration of the physical topology of the networking for the agricultural cloud platform. Security equipment such as firewall, isolation gap, the audit system of operations and maintenance, and the audit system for database should be installed next to the convergence layer. Firewall is used for the security isolation between different business systems in the same network, whereas the isolation gap is used for the secure exchange of data between different networks isolated by MPLS VPN and for secure data exchange on the cloud platform.

Network load balancing is divided into link load balancing and local load balancing (Dupont et al. 2012; Zhao 2017), and the overall logic diagram is shown in Fig. 14.2. As shown in the figure, the mobile Internet dedicated line and the telecom Internet dedicated line are connected to the link load balancer, which makes multi-Internet access available by controlling the trafficking and bandwidth of all Internet links. Link load balancer virtualizes multiple Internet lines to ensure that users can access both the internal and external resources from the best lines. The interruption of any ISP line will not affect the service. Additionally, the ISP access line can be extended seamlessly through the link load balancer.

Outbound traffic load balancing: when the traffic from the agricultural cloud platform of Zhejiang University reaches the link load balancer, the best exit link is selected among various links via detection results to improve the user experience.

Inbound traffic load balancing: in order to allow mobile users and telecom users to visit the application system for Internet access through different links, intelligent

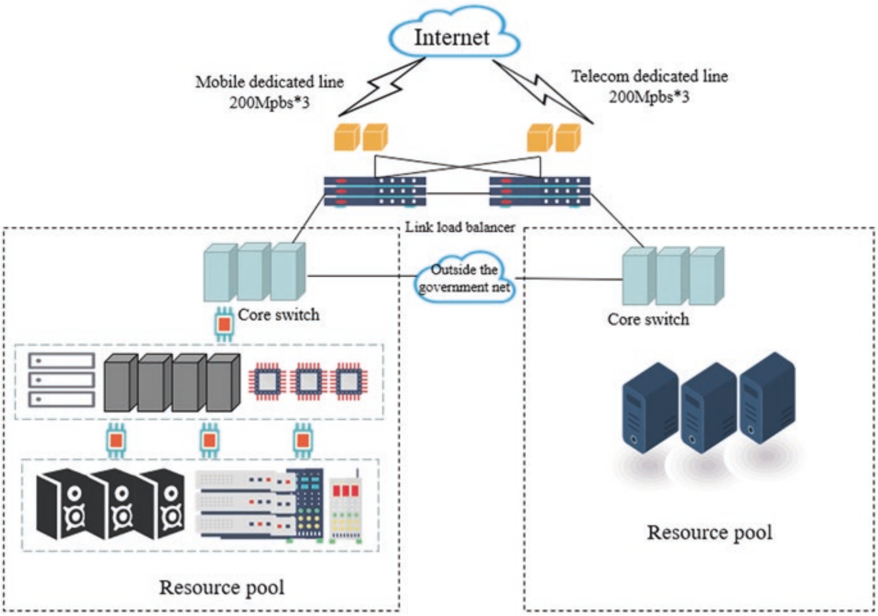

Fig. 14.1 Physical topology of the networking for the agricultural cloud platform

DNS resolution translates the domain names of different users into different public network IP addresses to accelerate application access, hence improving user experience.

14.2.2.2 Network Virtualization Design

In order to provide a network environment with improved performance and larger two-layer domain, the new core switch and sink switch in this project are respectively virtualized into a logical device through switch virtualization technology, hence reducing device nodes and simplifying configuration. STP + VRRP protocol in the traditional deployment mode is replaced by the cross-device link aggregation technology, which simplifies the network topology and makes it more scalable. At the same time, its fault convergence time in milliseconds makes it easier to achieve virtual machine migration, as shown in Fig. 14.3.

After the two-layer transparent transformation, the convergence access layer of the cloud computing platform becomes a transparent two-layer network. Different services (virtual servers) are connected to different two-layer VLANs, but the same service (virtual servers) can be flexibly deployed and migrated in different network partitions, which meets the requirements of cloud computing. At the same time, VPN label exchange and routing forwarding are carried out above the aggregation layer, hence ensuring the security isolation of different services (virtual servers).

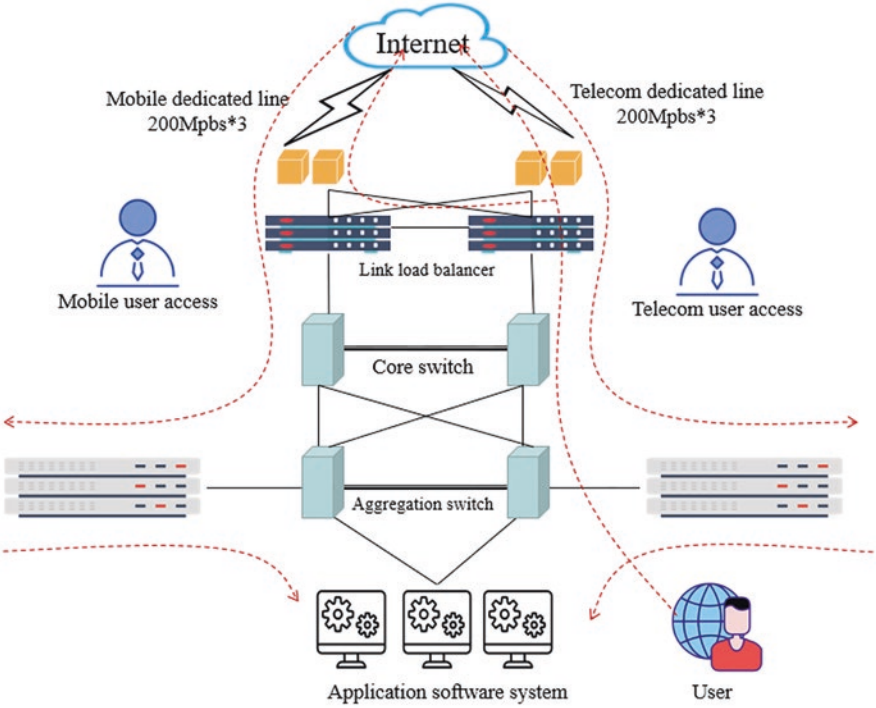

Fig. 14.2 Network load balance diagram

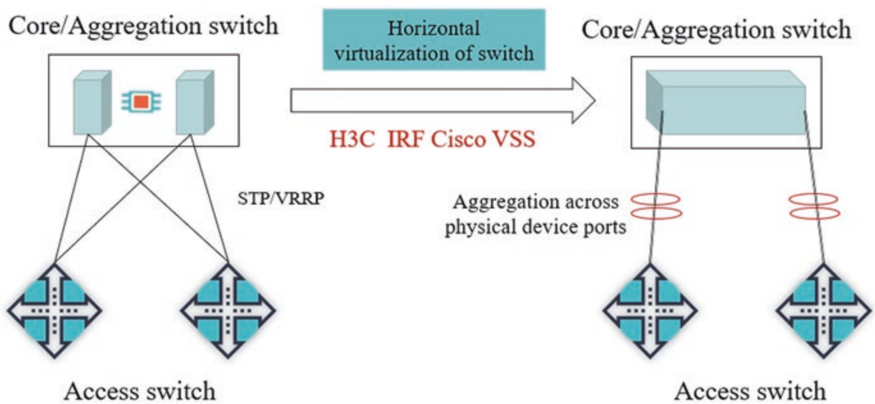

Fig. 14.3 Horizontal virtualization of the switch

14.2.3 Application System Analysis

According to the characteristics of specific operations, the application system hosted by the agricultural cloud platform is divided into three categories: high traffic application system, large computing application system, and big data application system.

The high traffic application systems are web application systems, including the cloud platform for management, traceability system, and information query system. This type of application is characterized by simple logic and the disconnection of different requests. But the concurrency of requests can significantly vary depending on the specific characteristics. For example, traffic to the agricultural information network will soar during disastrous weather conditions. High-traffic applications require rapid response to a large number of unrelated concurrent requests. In this case, the application server is required to have a sufficient number of threads to respond to the requests, and the amount of calculation a single thread deals with is not too much. Thus, the task is not very demanding for the processing performance of a single CPU, and the requirement of computing power would be satisfied when sufficient number of CPU servers are provided, though they may not be highly functioning individually. The cloud platform adopts virtualization technology to deploy virtual machine as the application server for the high-traffic application system, and the multi-application server works in the load-balancing mode to improve user experience. Furthermore, the high traffic application system is not very demanding in terms of database, and the configuration of the general virtual machine would be sufficient.

Large computation application systems, including agricultural IoT integrated management platform, GIS geographic information system, visual monitoring system, and other complex information processing systems, are characterized by the large amount of computing, complex computing, large memory demand, and high demand for server computing performance. It is recommended that a single high-performance virtual server be configured. Large computation application systems are not demanding in terms of database, and general virtual machines would be sufficient.

The big data application system, according to the database storage mode, can be divided into file system and database system. Database system requires database servers with strong performance that provide sufficient CPU, memory, and IO capabilities to handle large amounts of data. Depending on the level of significance, the database server can be either virtual servers or physical servers. The logic of the application server is simple, and configuration is not demanding; thus, virtual machines should be sufficient.

14.2.4 Deployment of Application Server

Application servers can be deployed on virtual machine systems (VMS) and physical PC servers. When the load of the application server approaches the maximum performance of a single physical server, application servers can be directly deployed to the physical server, though they are generally deployed on virtual machines.

According to the availability requirement of the application system, there are three ways to achieve high availability in the virtual machine, namely, virtual machine thermal migration, virtual machine HA (high availability), and physical machine HA (high availability).

Virtual machine thermal migration is adopted to enable scheduled downtime maintenance operations. When the server needs to be turned off for maintenance, virtual machines on one physical server can be dynamically migrated to another physical server through such thermal migration, and thanks to dynamic migration process, operations will not be interrupted, and normal access will be maintained.

Virtual machine HA is used to cope with unplanned outages of common application servers. In the event of a server failure, the virtual machine HA will be adopted to automatically restart the virtual machine on other physical servers for failover. This process leads to a short outage, which is determined by the startup time of operating system on another physical server and the startup time of application system. The number of servers in virtual machine HA is less than half of that in the traditional cluster, which improves resource utilization while ensuring high availability.

For applications deployed directly on a physical server, availability assurance is provided through the high availability clustering software. It is worth mentioning that the MSCS (Microsoft Cluster Server) is configured on Windows and the VCS (Veritas Cluster Server) is configured on the Red Hat Linux operating system. The negative impact of outages is reduced and eliminated by deploying clusters with high availability to ensure rapid failover in the event of server failure.

The make the application platform more scalable and reliable and to allow the server in the cluster to allocate load, so that customers maximize the application server investment value, the hardware load balancing device is deployed on the application server services and applications to provide the best scalability and performance.

14.2.5 Key Database Deployment

As the data processing platform of the operation system, the database service area is highly demanding in terms of the I/O processing capacity, memory, and CPU; thus, high-performance rack-like server deployment should be adopted. Databases of different operation systems can share the same cluster through multiple instances, and database management systems that are not demanding with regard to server performance can be deployed on virtual machines.

Database server is the core node of the operation system. To ensure its high availability, at least two physical servers or two virtual machines should be used as HA. For instance, the application HA ensures the high availability of the database management system that has been deployed on virtual machines. The high availability of database management systems deployed on physical servers can be guaranteed via VCS MSCS or its own clustering software (RAC).

14.2.5.1 Statistical Machine Learning

As the most important branch of artificial intelligence, statistical machine learning represents a field of research formed by the combination of probability statistics, information theory, optimization method, and calculation theory. Base on known data, statistical machine learning can predict and analyze unknown data by constructing a probabilistic statistical model that describes data features. Therefore, the basic assumption of statistical machine learning is that similar data have certain statistical regularity. Since similar data share statistical regularity, they can be dealt by probability statistics, that is, the characteristics of data can be described in the form of random variables, and the statistical pattern of data can be described by probability distribution.

The basic framework of statistical machine learning, which focuses on the existing data, constructs a mathematical process to acquire the effective features (feature design) in data and the potential association between them (information organization), i.e., feature expression. Based on feature expression, the classifier is designed to predict the unknown data. Statistical machine learning is focused on a variety of data, including crop spectral signals, peripherals of pests, or other types of data, such as audio frequency. In addition, statistical machine learning consists of supervised learning, unsupervised learning, semi-supervised learning, and reinforcement learning.

14.2.5.2 Clustering Algorithm

Clustering is a process of dividing a data set into several classes according to its own characteristics. The result of the division is that the data similarity within the same class is as large as possible and the data similarity between different classes is as small as possible, so as to discover the internal structure of the data set.

- Stand-alone clustering algorithm

Traditional clustering algorithms can be divided into partition clustering, hierarchical clustering, density-based clustering, model-based clustering, and grid-based clustering.

Sampling-based clustering algorithm is different from the original clustering algorithm based on the whole data set. Instead, only one sample of the data set is required, and the algorithm extends to the whole data set. As it only needs to cluster smaller data sets, the required clustering time and storage space are significantly lowered.

Clustering algorithm based on dimension reduction features two dimensions in the measurement of data size: the number of variables and the number of instances. Both dimensions are large in values, which might be problematic when analyzing the data. Therefore, it is necessary to implement data processing tools and preprocess data sets before applying clustering algorithms, so as to gain a better understanding of the knowledge contained in the data. Here, dimension reduction can be adopted to solve this problem. The goal of dimension reduction is to select or extract the optimal subset of data features with relevant characteristics based on a predefined criterion. Depending on the criteria used, the selection of a subset of features can eliminate extraneous and redundant information. Furthermore, such selection or extraction can reduce space needed by the sample. For large data sets, dimension reduction is usually used before adopting clustering algorithms to avoid the problems that high dimensions may bring.

- Multi-machine clustering

In parallel clustering, processing of big data requires parallel computing to obtain results within a reasonable time. Parallel clustering divides the data and distributes it on different machines, thus improving the clustering speed of a single machine and the scalability.

MapReduce-based clustering. MapReduce is a task partitioning mechanism that distributes tasks across a large number of servers. The Map phase breaks down a task into smaller subtasks and assigns them to different servers for execution. It is worthy noticing that the Reduce phase merges the results of subtask execution.

14.3 Application of Big Data

14.3.1 Overall Construction Scheme of Cloud Platform

Taking the agricultural IoT, big data, and cloud platform of Zhejiang University as an example (Nie 2012; Yue et al. 2019), such agricultural cloud platforms mainly perform the following three functions:

- The effective collection of the visual field information of the Agricultural Science and Technology Demonstration and Application Base of Zhejiang University. Such information can be analyzed remotely and controlled intelligently.
- Unified management of cloud service platform is implemented for the base, though system servers may not be installed there. Equipped with the agricultural IoT information sensing device and intelligent control system, the system transmits data to the cloud service platform via Internet or 3G/4G/5G, and the cloud service software subsystem is formulated according to the actual production situ-

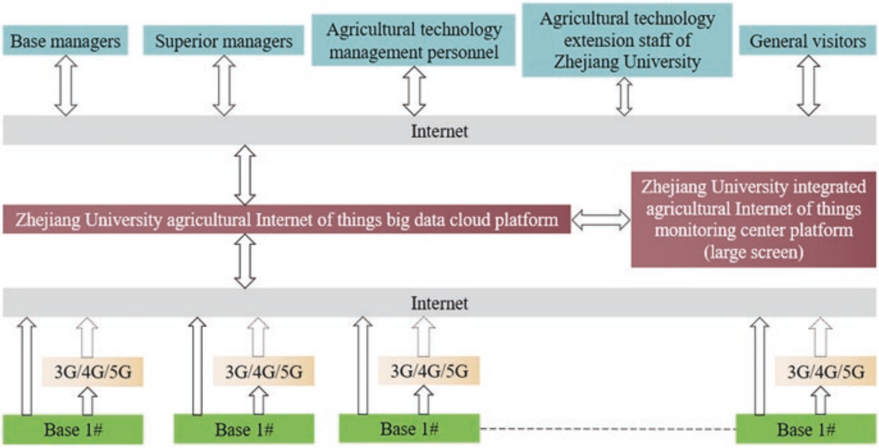

Fig. 14.4 The overall structure of the project plan

ation of the base. Apart from this, unified management also provides remote intelligent management for the base.
- Full display of the level of popularization and application of agricultural science and technology in Zhejiang University.

On this basis, a cloud service platform with the overall framework (illustrated in Fig. 14.4) is proposed. Agricultural production sites do not require the setting up of servers, and all information and intelligent control are operated through remote cloud. The production sites only need to be connected to the Internet.

The new platform for research on rural development will be connected to the agriculture-related sites of the University distributed all over the country. All kinds of visual information and intelligent control systems of each site are connected to the cloud service system of Zhejiang University via Internet or 3G/4G/5G wireless connection, and remote cloud services such as the intelligent management system of production, e-commerce system, and product traceability system are customized in the cloud service platform. Management staff of the sites can directly access the cloud platform of Zhejiang University through private login and then enter the formulated software service system to achieve information monitoring and intelligent control; hence, the real-time monitoring of subordinate sites in the campus will no longer be subject to whether the local servers of the base are functioning. The production sites have been also exempted from the cost of setting up servers for round-the-clock operation.

Developed on the basis of this framework is the cloud service software platform, which mainly provides management systems for crop farming, aquaculture, and livestock farming. Cloud service software platform mainly provides intelligent management cloud services for production sites and also sets up e-commerce platforms and traceability platforms. Users in the production sites can get customized services on the cloud platform, and customized systems are also available. In a comprehensive production site that features crop farming, livestock farming, and

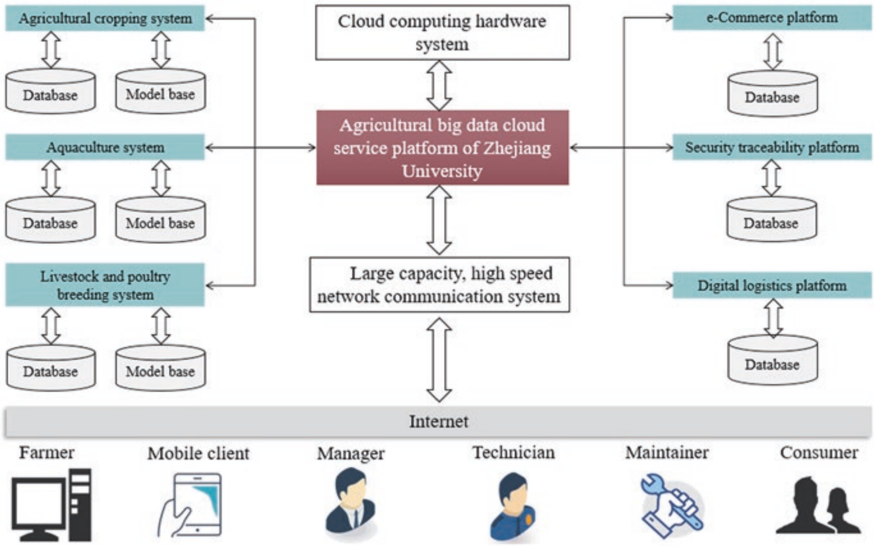

Fig. 14.5 The construction structure of cloud service platform

e-commerce, three corresponding systems can be customized, and site-by-service model is formed. Management staff can log in the management system under their own authority to obtain remote monitoring and intelligent management cloud services. Administrators or technicians can review the situation of each production site that has been connected to the platform and help them set the management parameters and participate in the intelligent management of the site. System maintenance personnel can diagnose and maintain the related equipment remotely through their special authority (Riondato and Upfal 2014). The basic framework is shown in Fig. 14.5.

When the cloud service platform is built, the management and display software platform of the university will be used for the display and management of production sites all over the country.

Production sites connected to the cloud platform include businesses, cooperatives in different regions, and different types of production units. Therefore, two retrieval modes are provided on the platform to view the distribution and real-time status of IoT systems by category and region (Chen et al. 2015; Sun 2019).

14.3.2 Overall Plan for the Construction of Production Sites

Production sites constitute one of the data sources for the cloud service platform, and the big data cloud service platform is built through a variety of large databases (Wang et al. 2014; Xie 2018). Figure 14.6 offers an illustration of the basic structure.

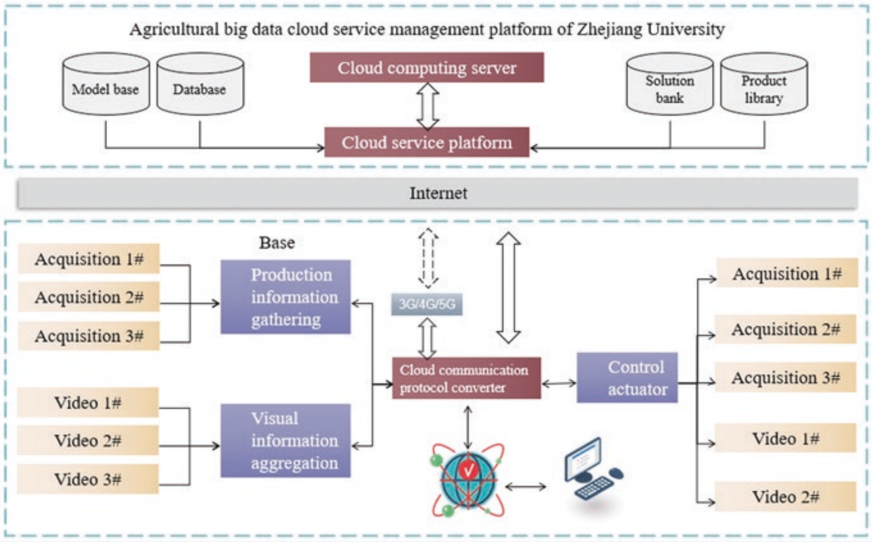

Fig. 14.6 The overall plan of IoT and remote cloud service for production sites

As shown in Fig. 14.6, production sites come with Internet information collection equipment, intelligent control equipment, and visual monitoring equipment. Additionally, the above systems will be converged through the bus and the level, protocol conversion, conversion into Ethernet communication interface, and unified access to the Internet network. If a production site cannot directly access the optical fiber network due to constraints, 4G wireless communication equipment will be used to transmit all information of the production site to the cloud service platform of Zhejiang University. Considering the traffic cost, videos are accessed in the cloud, but not stored in the cloud; rather, it is stored in the local video server. Other agricultural production information and intelligent control strategies are stored in the cloud service platform, and users can get direct access to and control of the cloud remotely through the network.

Cloud computing, a new computing resource utilization model, distributes computing tasks over a pool of resources made up of a large number of computers, enabling various applications to obtain computing power, storage space, and information services as needed. According to the degree of service implementation, currently, cloud computing mainly includes IaaS, PaaS, and SaaS business models.

Infrastructure as a Service (IaaS)

IaaS layer provides virtual hardware resources in the mode of services to virtualize and pool infrastructure resources (computing, storage, network bandwidth, and so on), facilitating dynamic allocation, redistribution, and recovery of resources. At present, resource pools are mainly divided into four types, each dedicated for computing, storage, network, and content that include software and data. In terms of services, IaaS provides computing and storage resources, including virtual server and storage space, application server, database management system, and other application system operating environment (Hassan et al. 2014).

Platform as a Service (PaaS)
The PaaS layer is primarily a platform for the development, testing, and execution of applications. Users can quickly develop, test, and deploy applications based on this platform. PaaS relies on the cloud computing infrastructure to transform infrastructure resources into platform environment for users and applications. PaaS provides a software development and testing environment for different systems while incorporating system functions into a centralized SOA platform. Moreover, application service artifacts within the organization are reused and orchestrated, so that these service artifacts can be organized on demand. Typical portal platform services can provide users with customized development portals, allowing users to deploy the application within short periods of time.

Software as a Service (SaaS)
As shown in Fig.14.7, the typical usage of SaaS, which is provided as a service, is that users use the software on the Internet through a standard WEB browser; hence, no purchase is necessary, and consumers can simply rent the software on demand and apply it directly.

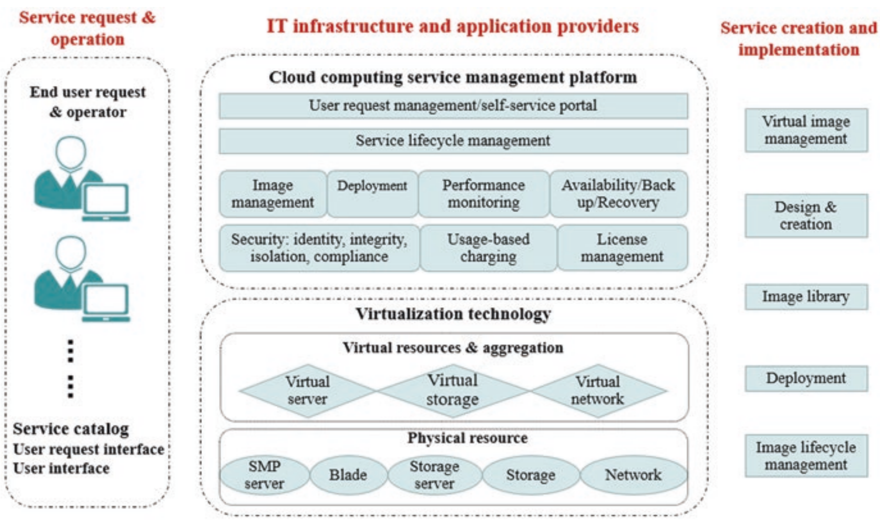

Fig. 14.7 Overall topology of the cloud computing platform

14.4 Summary

This chapter offers a specific analysis of the IoT platform for integrated management of agriculture that is based on cloud computing and big data, including the overall system function, structure, composition, and key technologies. We see that cloud computing technology and innovative models are combined to create a cloud platform with unified standards, diverse functions, and stable, safe, and reliable systems, thus enabling data interaction, remote management, and cloud computing services. The major components of the cloud platform include a system based on a three-tier architecture, a system with a large amount of trafficking, an application system with a large amount of data processing, and an application system with a large amount of calculation. Additionally, thanks to the technical advantages of cloud computing and big data, the cloud platform achieves offline user data sharing, management and monitoring of data, seamless traceability, and digital monitoring of logistics.

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