Chapter 14
Role of CPS in Smart Cities

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14.1 The Background and the Goal of the Smart City

Globally, 55% of the world's population lives in urban areas in 2018, and this value is expected to increase to 68% by 2050 (United Nations 2018). The city is gradually becoming the most significant carrier of current economic society, in which critical infrastructures (CI), such as transportation, energy, and healthcare, are backbones for the operation of cities. In the meantime, it's not uncommon in our cities to see traffic congestion, shortage of resources, or environmental pollution, with the ever-growing population of cities and. Besides, global warming and climate change also have a crucial impact on urban life, through events such as frequent urban floods. Those series of problems have troubled municipalities as well as residents to find some optimal solutions for a long time. With the advent of the fourth industrial revolution, technological advancements such as Cyber-Physical Systems (CPS), the Internet of Things (IoT), cloud computing, cognitive computing, etc., are combined to make our twenty-first-century cities more instrumented, interconnected and intelligent.

Smart city construction is now a world-wide hot topic. Although there is no universally accepted definition of a smart city, generally speaking, a smart city is a concept that brings together infrastructure and information and communication technology to improve the quality of citizens' life as well as the efficiency of existing infrastructure, therefore achieving a more sustainable and resilient urban environment. Moreover, an increasingly aging society urgently needs a smart city solution. Currently, we can see applications of some subdivisions of the smart city, e.g. smart grids or intelligent transportation systems (smart transport). Sensing and optimization control of one component alone is still challenging, and the challenge is exponentially increased in a smart city setting where all these components are

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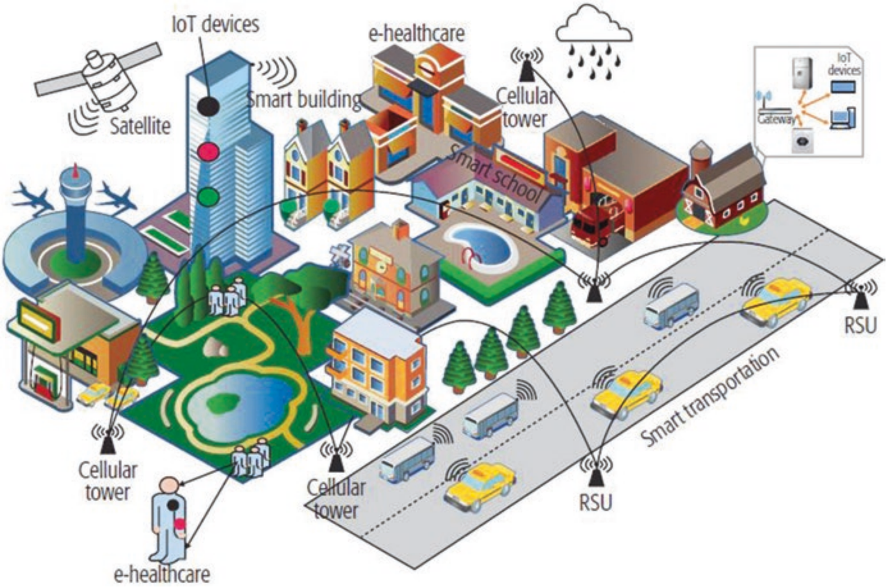


Fig. 14.1 An illustration of IoT based smart city (Mehmood et al. 2017)

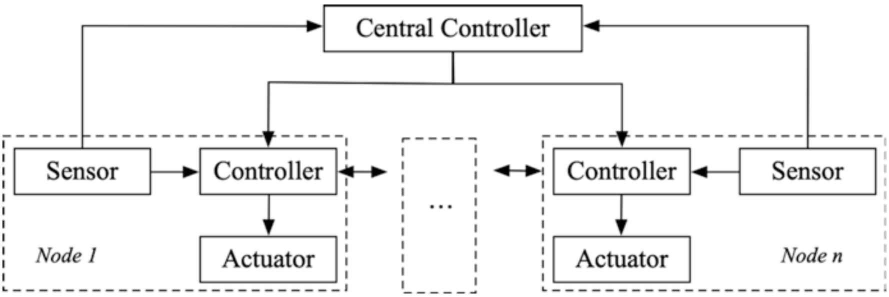


Fig. 14.2 Basic structure of CPS

working interdependently. Therefore, from conception to real-world application, it still has a long way to go.

When speaking the engineering practice of smart city, recent year's concerns are more related to 'IoT' (see Fig. 14.1), which is an enabling technology for CPS. As a highly complicated and multidisciplinary setting, CPS targets integrating computing services and physical systems to provide coherent and intelligent services (Lee et al. 2015), through a mixed system integrated with computation, communication, and control. The merging of IoT and CPS into closed-loop, real-time IoT-enabled cyber-physical systems is seen as an important future challenge.

In the same way the Internet changed our lifestyle for interaction between people, CPS will change our interaction with the physical world. In Fig. 14.2, a basic structure and information flow of CPS between different nodes is shown. The following section will illustrate the key enabling technologies including communication and sensing technology, computation and cognition technology, and control technology. A smart city emphasizes efficient information processing abilities, integration of information resources and management capabilities so that all parts become more coordinated. As such, CPS has a huge role to play in contemporary smart city applications (Ghaemi 2017) Therefore, it is an innovative and exciting emerging field that has numerous applications in smart cities.

In this chapter, we first reviewed the global-wide smart city construction in Sect. 14.2; relevant key technologies are discussed in Sect. 14.3; Some Examples of CPS applications in smart cities are listed in Sect. 14.4; sample practices of smart transport and smart construction in smart cities are respectively discussed in Sects. 14.5 and. 14.6; challenges and future trends are proposed in Sect. 14.7; summary of this chapter is described in Sect. 14.8.

14.2 World-Wide Development of Smart City

The development of the smart city requires three stages, (1) sensing of the city; (2) real-time awareness of the city; (3) real-time control of the city. Since IBM proposed a 'smarter planet' in 2008, many countries have adopted 'smart city' as the national-level strategy to lead a more livable urban life. In the published 'Global trends 2030: alternative worlds' by the National Intelligence Council of America, the "smart city" is among the most influential 13 technologies (National Intelligence Council 2012).

'Industry 4.0' as a national strategic initiative proposed by Germany, aims to drive digital manufacturing forward by increasing digitization and the interconnection of products, value chains, and business models. A typical case of this perspective is shown in Fig. 14.3(a), in which production, engineering, smart grid, etc., are considered as a whole. Additionally, Singapore has already put trials in place of sustainable estates, remote healthcare, smart buses, self-driving vehicles and so on. Furthermore, 'Virtual Singapore' (see Fig. 14.3(b)) that under construction, which is a dynamic three-dimensional (3D) digital replica of Singapore built on topographical as well as real-time, dynamic data. In the third stage, until in 2015, cognitive computing attracts people's attention (Kelly 2015), to simulate human thought processes in a computerized model. That's a new era of current smart city construction, from sensing to awareness benefited from CPS. Through a variety of established technologies such as data mining, pattern recognition, and natural language process, we can build systems that mimic how the human brain works. For example, ET city brain (see Fig. 14.3(c)) established in Hangzhou (a city of China) has become a new infrastructure for this city, by using artificial intelligence and advanced algorithms to analyze a large amount of data and turn them into actionable information in real-time speed.

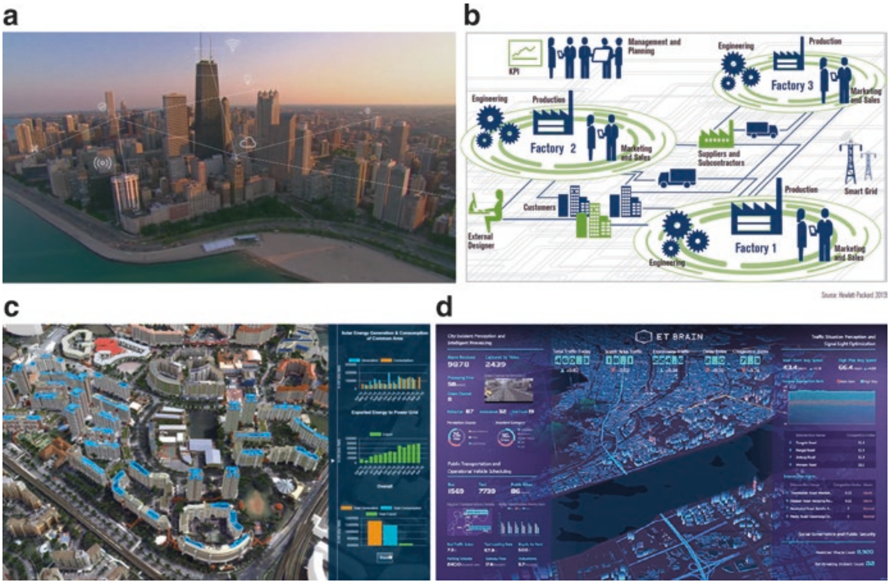


Fig. 14.3 Some smart city cases: (**a**) smart Chicago; (**b**) Germany; (**c**) Virtual Singapore; (**d**) ET City Brian

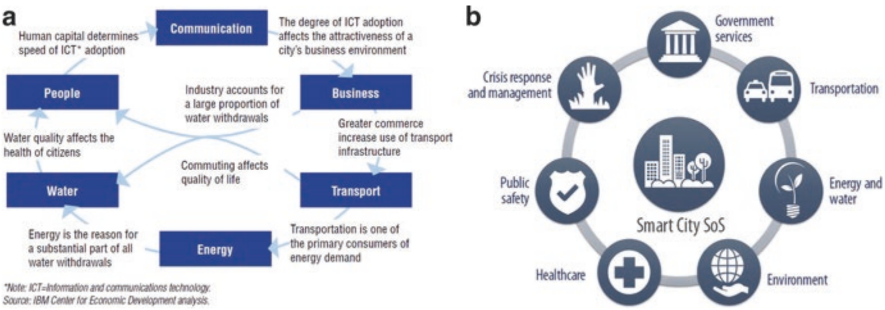


Fig. 14.4 Interdependency of CI, (**a**) Interrelationships between core city systems (IBM 2018); (**b**) Smart city SoS (Cavalcante et al. 2016)

Not restricted in the above-mentioned cities, Chicago (see Fig. 14.3(d)), Atlanta and Dallas, as well as European cities like Amsterdam, Manchester, Stockholm, and Helsinki, have also done some constituents implementations of the smart city. Use cases such as smart lighting, weather sensors, traffic monitoring and control, energy-efficient demand response are omnidirectional coverage over the city.

A city is a 'system of systems (SoS)', which is facing interconnected challenges (IBM 2018), see Fig. 14.4(a). The interconnected relationship between the critical infrastructures (CI) is difficult to model and control, and cascading failure is easy to happen with one component's failure. The main elements of a smart city can be seen in Fig. 14.4(b). A practical application of smart city relies on collaborating smart systems that interact, communicate and share information with each other, allowing for cross-domain usages of services. Furthermore, the commercialization of fifth-generation (5G) cellular network technology and supercomputers make it possible for near real-time information transfer and control, paving the way for the crucial real-time coordinate control of CPS.

From the previous descriptions, we concluded some key questions of smart city, that can be addressed through proper deployment of CPS: (1) accurate modeling and real-time simulation of the city, such as traffic system and power system, (2) coordinate control methodologies between interdependent infrastructures, (3) autonomous control without human interventions.

14.3 The Key Technologies of CPS in Smart Cities

CPS integrates computing, data analysis, communication and control with physical processes that are inherently uncertain, vulnerable to hackers and natural adversities. Figure 14.5 briefly overviews the essential processes of CPS:

Communication: high-speed communication using wired/wireless network
Sensing: monitoring of physical world events
Computing: processing and analysis of sensed datasets
Cognition: machine learning to make system thin like humans
Autonomous Control: responding in real-time without human intervention

14.3.1 Communication and Sensing Technology

Types of communication can be generally categorized as Human to human (H2H), Human to machine (H2M), Machine to human (M2H), and Machine to machine (M2M). For current CPS in smart cities, M2M is more frequently used, such as well-known Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure(V2I) technologies to advance safety and convenience in transportation networks. Those types of

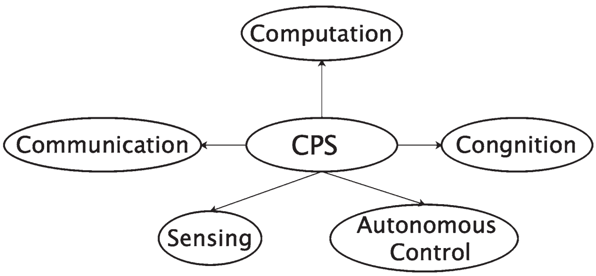


Fig. 14.5 Basic technologies of CPS

communication are generally via wire/wireless communication technologies, in which wireless-based smart city is concerned most.

Wireless radio access technologies are describing as followed:

(1) Cellular networks: also called mobile networks, such as GSM, CDMA. Any IoT application that require operation over long distances can take advantage of this technology; (2) IEEE 802.11, 802.16 (WiMAX), 802.22. IEEE 802.11: networks can perform as two different modes, as infrastructure networks and Vehicle Ad-hoc NETworks (VANETs); (3) Bluetooth: 2.4GHz frequency with a range of 50-150 m and data rates 1Mbps is an important short-range communications technology, especially for wearable products; (4) ZigBee: traditionally more in industrial settings, operating at 2.4GHz, targeting applications that require relatively infrequent data exchanges at low data-rates over a restricted area and within a 100 m range and data rates 250 kbps such as in a home or building, (5) 6LoWPAN (IPv6 Low-power Wireless Personal Area Network). Rather than being an IoT application protocols technology such as Bluetooth or ZigBee, 6LoWPAN is a network protocol that defines encapsulation and header compression mechanisms.

Comparison of different aspects of PAN, LAN, MAN, and WAN, as well as some possible applications in the framework of smart city, are shown in Table 14.1. Moreover, there is a consensus between academia and industry that 5G will make smart cities especially smart transportation closer to reality for highly popular mobile devices. Communication constraints induced by networks include, but not limited to (Garcia et al. 2018): network-induced delays, data packet dropout (data losses/packet losses), data packet disorder, quantization error (data quantization, quantization effect), time-varying network topology, network channel fading, time-varying network throughput.

Table 14.1 Comparisons of some wireless networks

Type	Standards	Typical range	Data rate	Applications example
Personal Area Network (PAN)	Bluetooth	2–10 m	1–3 Mbps	Smart wearable devices
	ZigBee	10–100 m	20–250 Kbps	Smart meters and readers Wireless sensor networks
	NFC	≤ 1 m	106 Kbit/s, 212 Kbit/s, or 424 Kbit/s	Mobile payment
Local Area Network (LAN)	IEEE 802.11 (WiFi)	30–100 m	1–11 Mbps	Smartphones, cameras, sensors
Metropolitan Area Network (MAN)	IEEE 802.16 (WiMAX)	≤50 km	70 Mbps/sector	Wireless inter-network connectivity
Wide Area Network (WAN)	Cellular (UMTS, LET, 5G)	Worldwide	5G: 1GPbs	Connected vehicles and autonomous vehicles

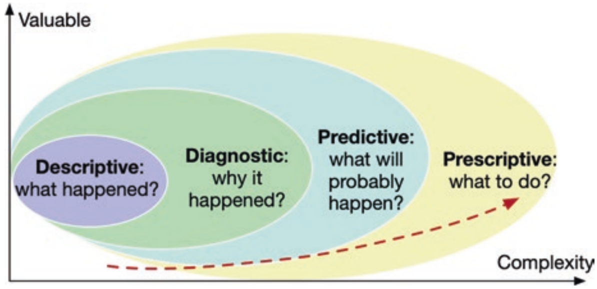


Fig. 14.6 Big data analysis

14.3.2 Computation and Cognition Technology

This part is most related to the 'data-driven' analysis performed after communication and sensing from the city that augments the 'intelligence' of the city. Four general stages of such big data analysis are: descriptive, diagnostic, predictive and prescriptive (Hashem et al. 2016) (see Fig. 14.6). Artificial intelligence (AI) learns how people use cities, optimizing infrastructure for cities, and improve public safety.

With the communication and sensing technologies, different types of data such as spatial and temporal data, time-series data, stream data, and multimedia databases can be obtained (Al Nuaimi et al. 2015). The explosive growth of data, from terabytes to petabytes, drives us to explore massive data sets for knowledge. One major approach is data mining, an interdisciplinary subfield of machine learning, statistics and database systems, with an overall goal to extract useful information from a dataset and make the decision of what qualifies as knowledge, also called knowledge discovery in databases (KDD). This knowledge could be non-trivial, implicit, previously unknown or potentially useful. Anomaly detection, association rule learning, clustering, classification, regression, and summarization are among the six common classes of tasks. Steps of a typical KDD process can be seen in Fig. 14.7.

Another smart city-related key technology is deep artificial neural networks also known as deep learning. Deep learning as a subset of machine learning methods can come in different architectures including deep neural networks, convolutional neural networks with application in a variety of fields including computer vision, speech recognition, etc. More specifically, reinforcement learning (RL) handles the problems of how agents take actions in an environment to maximize some notion of cumulative reward, i.e., a balance between exploration and exploitation. One of the most discussed limitations of deep learning is the fact that we don't understand how a neural network arrives at a particular solution.

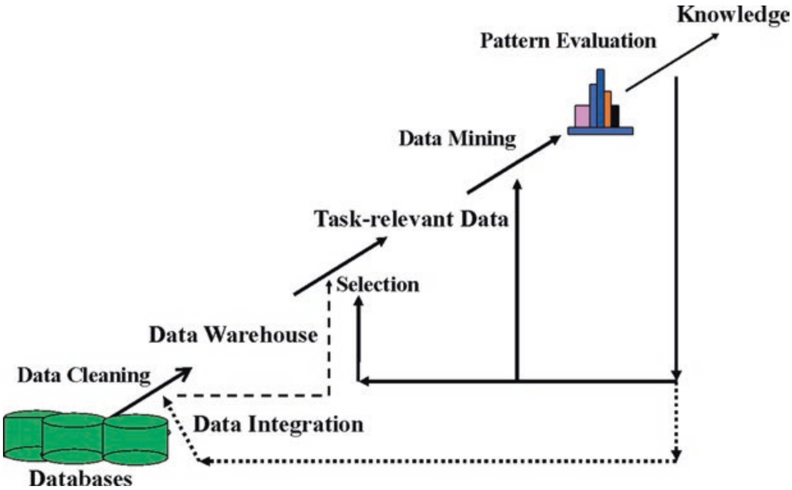


Fig. 14.7 Steps of the KDD process

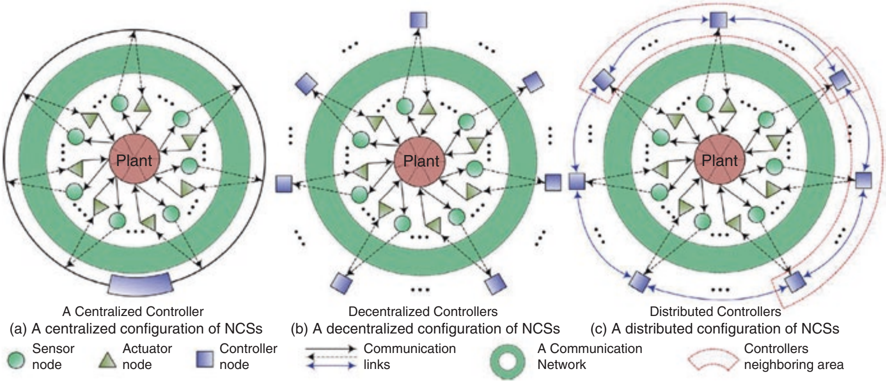


Fig. 14.8 Three general configurations of NCSs (Ge et al. 2017)

14.3.3 Autonomous Control Technology

As the third generation of control systems, modern control systems are increasingly adopting networked control frameworks such as power grids, transportation networks, and water networks. Networked control systems (NCSs) are systems whose control loops are closed through communication networks such that both control signals and feedback signals can be exchanged among systems components (sensors, controllers, actuators, and so on) (Pearl 2019, Zhang et al. 2016), see Fig. 14.2.

Generally, there are three configurations of NCSs (Fig. 14.8):

- Centralized configuration. This approach takes advantage of full knowledge of the system, in which suitable data fusion methods are necessary,

- Decentralized configuration. This approach utilizes local information to make a decision, distributed controller nodes do not share information with neighboring nodes.
- Distributed configuration. In this approach, information of each subsystem is exchanged among system components using a shared communication network. Meanwhile, a large number of simple interacting units that can be physically distributed and interconnected to others to coordinate their tasks for achieving a desired overall objective. 'cooperative control'.

14.4 Examples of CPS Applications in Smart Cities

With the emerging technologies of communication, computation, and control, applications such as smart grid, smart water management, smart city safety, smart transport, smart construction, etc., make a city "smart". That different smart components make our city an interdependent system, which can also be seen as a "system of systems", to provide a sustainable, safe and environmentally friendly urban life. Examples of these applications are as follows:

- ***Smart Grid:*** As a network of transmission lines, substations, transformers and more that deliver electricity from the power plant to city homes or offices, the smart grid provides more efficient and safe transmission of electricity. It can help ensure reliability, reduce peak demand, as well as integration with renewable energy.
- ***Smart water management:*** by applying sensors, smart meters, monitors, GIS and other infrastructures, real-time solutions can be implemented and broader networks can work together to reduce current management challenges.
- ***Smart Cities Safety:*** innovations in the IoT are increasingly improving the safety of city inhabitants. New services such as remotely connected CCTV and automated incident detection allow a quicker response to threats.
- ***Smart Transport:*** also known as Intelligent Transportation Systems (ITS), in which information and communication technologies are applied to road transport components, including infrastructure, vehicles, and users, for traffic and mobility management, as well as for interfaces with other modes of transport (European Union 2010).
- ***Smart Construction:*** a highly integrated and collaborated construction system should be proactively self-adaptive to the demand of changes in design, procurement, and construction, by relying on Building Information Modeling (BIM), Internet of Things (IoT), Artificial Intelligence (AI), Cloud Computing, Big Data, etc.

In the next section, we will introduce smart transport and smart construction in the smart cities for their individual concepts, roles, key techniques and etc.

14.5 Smart Transport in Smart Cities

In this section, we present smart transport as a vivid example application of CPS in smart cities. Deployment of smart transport in smart cities provides unique precision and flexibility in interaction and coordination for state awareness and real-time decision-making. Some key technologies are demonstrated as followed.

14.5.1 System Modeling: Online Microscopic Traffic Simulation

Smart transport in smart cities aims to integrate the information from real-time traffic variables measurements (flows, speeds, and occupancies) with microscopic traffic simulation, which focus on the reproduction of the movements of individual vehicles. An online microscopic traffic simulation model, FLOWSIM is presented. FLOWSIM uses fuzzy driver behavioral process from the originally off-line simulation (Wu et al. 2000), and the integrated real-time traffic surveillance data as the input for system simulation. Through online microscopic traffic simulation, the model can estimate travel time, predict network state, detect incident as well as simulations of emissions and energy, to minimize congestion, travel time and emissions.

FLOWSIM includes a sensing layer, a fusion layer, an application layer, and a presentation layer. Due to the variety of ways to obtain traffic data, such as video obtained from video surveillance, semi-structured/unstructured data of pictures, streaming data obtained by geomagnetic circle, GPS data of taxis, etc. Data structure, dimension, density, and characteristics are different, and as a result, cross-domain fusion with real-time traffic data is technically difficult. FLOWSIM applies deep neural network technology to identify standardized data. The microscopic simulation model also can predict the influence of traffic events (such as traffic accidents, extreme weather) online (see Fig. 14.9), therefore enhancing traffic guidance and emergency management.

The development and application of online traffic simulation technology is based on the full exploitation of big traffic data, real-time reproduction of road traffic demand and operational status, prediction of short-term traffic trends, and accordingly supports government decision-making through providing real-time information about public travel, improving the convenience and experience of public travel.

14.5.2 Data Mining of Driver Behavior

Behavior and interaction patterns among traffic participants, namely drivers, pedestrians, and bicycles, are crucial factors in the modeling of the system. It requires a thorough understanding of the diverse driving styles among drivers (Qi et al. 2016)

Fig. 14.9 Real-time microscopic traffic simulation: FLOWSIM

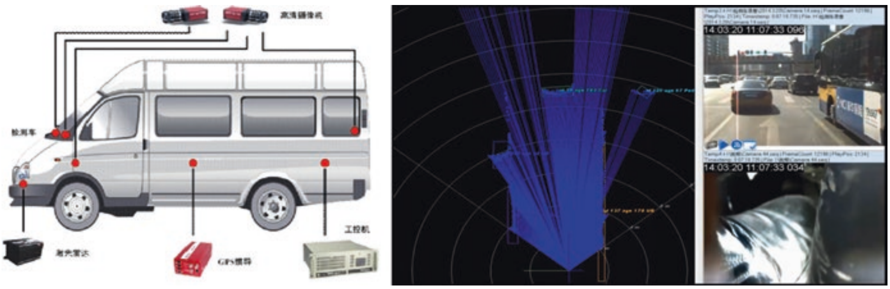


Fig. 14.10 Driving behavior's data collection equipment

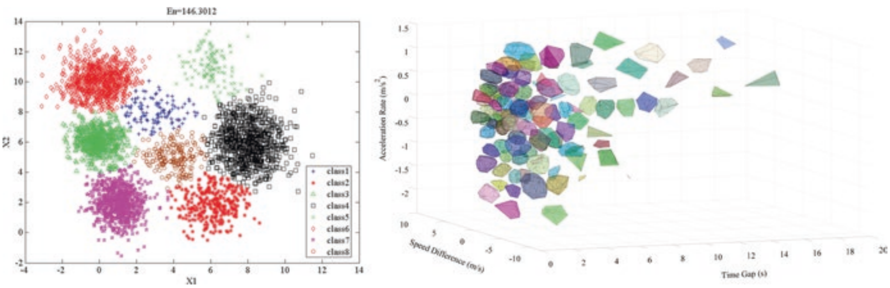


Fig. 14.11 Clustering of different driving behavior

as well as route choices (Xu et al. 2019). Driving behavior data can be collected via a self-developed comprehensive inspection vehicle (Fig. 14.10). To this end, participants from different groups of genders, ages, educational backgrounds, etc., need to be considered. Clustering algorithms can be used for the established driving style/ state/behavior model. A typical result by the fuzzy dynamic kernels C-means clustering algorithm can be seen in Fig. 14.11.

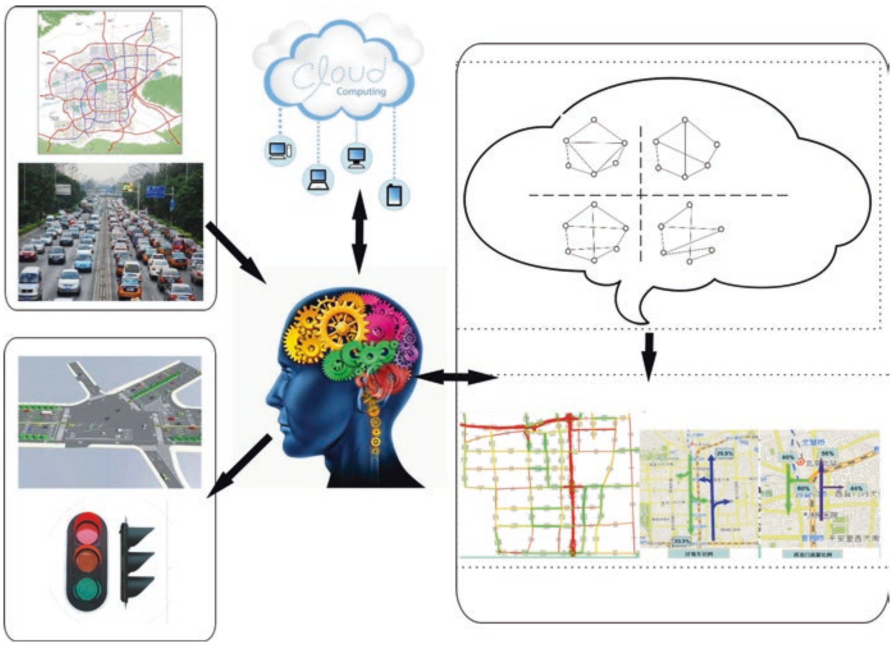


Fig. 14.12 Reinforcement learning of real-time signal control

14.5.3 Real-Time Traffic System Control

In order to enable efficient and accurate urban traffic system control, traffic signals also have to be taken into account. A wide range of investigations using reinforcement learning is presented that optimize traffic signals in real-time (see Fig. 14.12). Examples of these methods include Q-learning, DQN. Although these approaches have more impact in improving autonomous driving, still they are only investigated at the simulation-level, combined with traffic simulation tools, such as SUMO. Another approach is dynamic traffic flow guidance to realizing the equilibrium distribution of traffic flow. Based on the goal of maximizing traffic capacity, online traffic simulation can help the guidance process with dynamic OD and specific destinations.

14.5.4 Vehicular Ad-Hoc Networks (VANETs)

Communication via V2X (Vehicle to Everything) will transform our future urban roadway network into a self-organized and distributed control network, also known as VANETs (Fig. 14.13). However, in VANETs, the movement of the vehicle frequently causes network topology to changes and communication links to be disconnected. Vehicles not only play the role of sending and receiving information but also

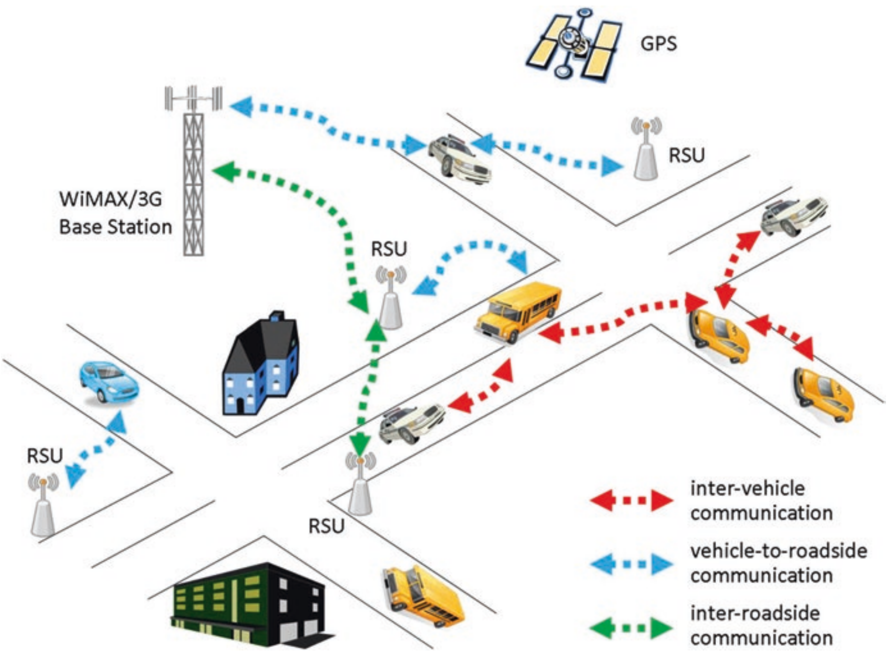


Fig. 14.13 An illustration of VANET scenario

in routing. Latency, packet loss rate, and network load will have a significant impact on the network operation, which is still a hot academic issue.

14.6 Smart Construction in Smart Cities

Construction is an important activity in the development and renewal of a city, involving buildings, landscape, and infrastructure (e.g. roads and bridges). Smart construction, therefore, is also a critical part of a smart city, directly influencing the decision making of urban development and management. This section illuminates the concept, components, key technologies and roles of smart construction in smart cities.

14.6.1 The Concept of Smart Construction

Smart construction promoting digital construction has been promoted in the construction industry worldwide in recent years. It is being regarded as a promising approach to solving the main issues occurring in the industry, such as low productivity, high accident rate, the shortage of labor, etc. However, a unified definition of smart construction still does not exist. Here, smart construction is described as a

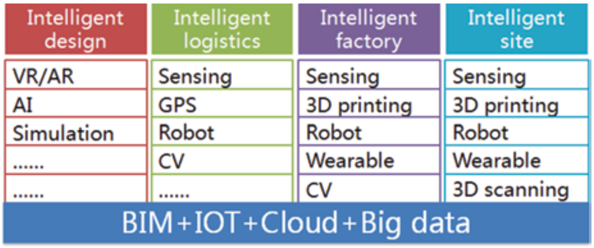


Fig. 14.14 The critical components and key technologies of smart construction

highly integrated and collaborated construction system that is able to be proactively self-adaptive to the changes in design, procurement and construction, relying on Building Information Modeling (BIM), Internet of Things (IoT), Artificial Intelligence (AI), Cloud Computing, Big Data, etc. This system integrates all stages of a construction project including design, procurement, and construction (including production and assembly), enabling intelligent collaboration among stakeholders. The target of smart construction is to make the construction process intelligent (flexible), efficient, safe and green.

14.6.2 The Critical Components of Smart Construction

The smart construction system is mainly composed of four critical components, i.e. intelligent design, intelligent logistics, intelligent production, and intelligent worksite (see Fig. 14.14), which work together. Intelligent design aims at efficiently and (semi-)automatically complete the design of a facility by referring to clients' requirements as well as those of intelligent production and assembly and make quick responses to any changes from clients, designers, producers, constructors, etc. Intelligent logistics helps manage the automatic procurement and transportation of raw materials and facility components for component produced/assembled in the factory and assembly/construction on site, and quickly responds to any changes from design, production and site. Intelligent production is a place to automatically produce facility components, and an intelligent site is a place to complete all construction/assembly activities to deliver a completed facility by using intelligent technologies. Figure 14.15 shows the flow for the intelligent transportation of precast components to support intelligent assembly in construction sites.

14.6.3 The Role of Smart Construction in Smart Cities

As mentioned earlier, smart construction is an approach to automatically and intelligently deliver a construction project which aims to make the process more flexible, efficient, safe, and environmentally friendly (see Fig. 14.16). This means smart

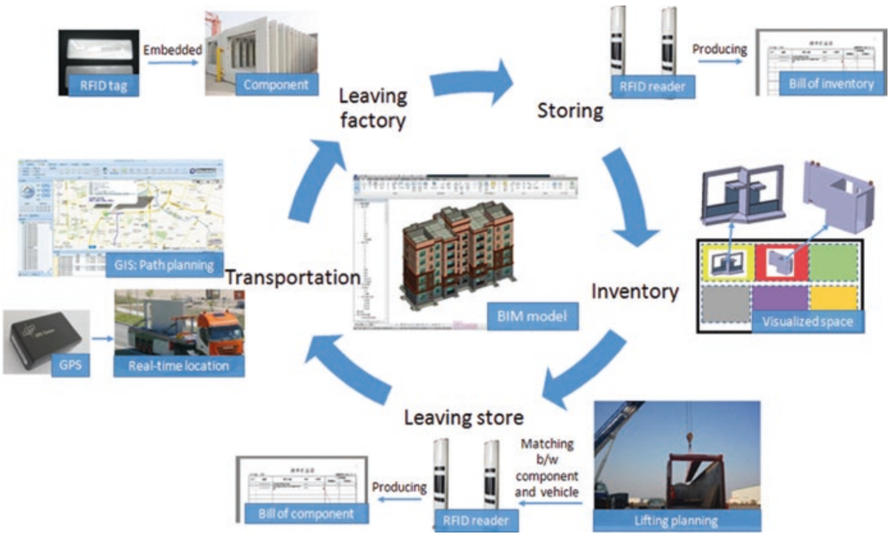
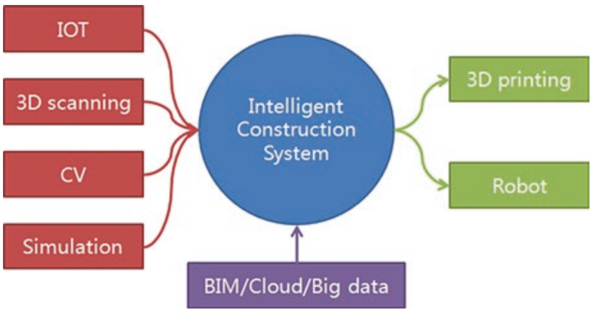


Fig. 14.15 A diagram for intelligent transportation of precast components

Fig. 14.16 The categories of key technologies of smart construction



construction is able to improve not only the productivity of the construction industry but also its safety level and sustainability. Meanwhile, due to the use of more and more intelligent devices, it will reduce the use of workers in construction sites. Thus, smart construction will change the future of construction and further serve the rapid development of smart cities in the future.

14.7 Challenges and the Future Trends of CPS for Smart Cities

With the rapid advancement and use of the Internet, embedded systems, wireless communication technologies, and novel control strategies, CPS will be the core of future smart cities to connect the virtual and real worlds. as shown in Fig. 14.17,

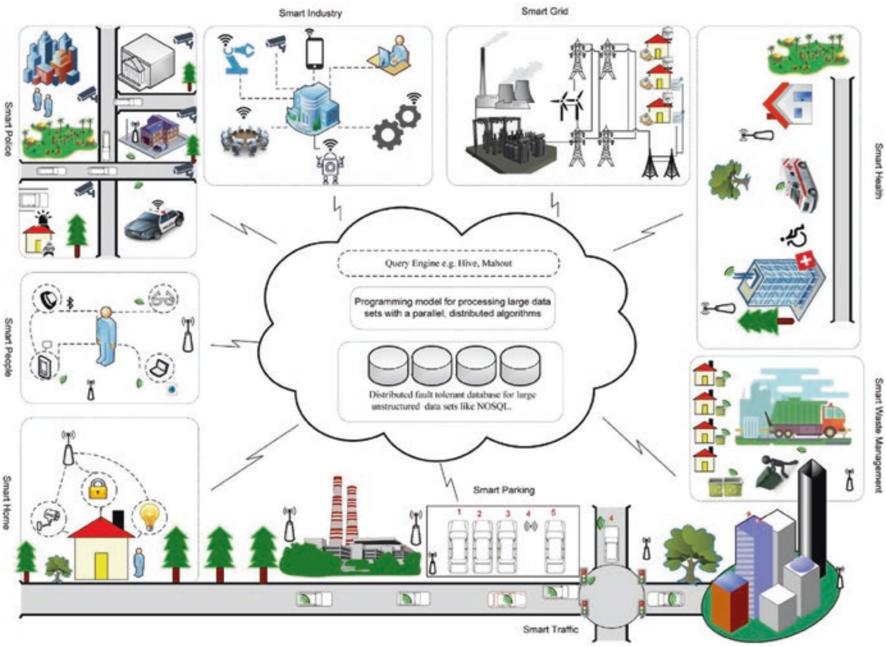


Fig. 14.17 Landscape of the smart city (Hashem et al. 2016)

CPS transpasses all aspects of smart city, and the research and application of CPS will be the crucial foundation of developing smart cities. However, multiple challenges exist and have to be addressed:

Theoretical foundation: lack of composition theories for heterogeneous systems, differences between discrete characteristics of computer and physical world continuity;

System design and verification: complexity, uncertainty and emergent behaviors make cross-domain interfaces and interactions difficult. And the cost of verification is high.

Guarantee the real-time and stability of CPS: for data blocking, delay, and packet loss. Furthermore, the vulnerability of CPS is also an issue, such as system overload-induced cascading failure.

Security, privacy and public awareness of CPS: Coupling of the information from cyberspace and physical world raises the problem of security and privacy, in which privacy enhancement technology, such as cryptographic operations, verifiable calculations, and data obfuscation.

14.8 Summary

CPS plays a vital role in the development of a smart city, which, if employed properly, will influence various aspects of social and economic life. The rapid development of communication, computation and control technologies facilitates this endeavor. This chapter provides the background and goal of smart cities, the worldwide development of smart cities, relevant key technologies of CPS, applications of CPS in smart city's smart transport and smart construction, as well as deployment challenges and future trends. As the key technologies of future smart city and future trends, CPS-based systems need to consider human integration into smart city applications, i.e., from CPS to HCPS, to enable a fully autonomous society. Moreover, real-time system modeling and cross-domain interactions also have to be solved. A more coordinated, intelligent and sustainable smart city will be seen with the further integration between cyber and physical systems.

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