Chimay J. Anumba
Nazila Roofigari-Esfahan *Editors*

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Chimay J. Anumba
Nazila Roofigari-Esfahan

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Chapter 1
Fundamentals of Cyber-Physical Systems

Amir Abiri Jahromi and Deepa Kundur

1.1 Introduction

Cyber-physical systems are permeating practical application to become an in-tegral part of manufacturing, healthcare, agriculture, transportation, energy systems, financial systems, defense and smart infrastructure amongst other application spaces. It is expected that cyber-physical systems in twenty-first century generate comparable innovation and drive for economic productivity and growth to the Internet revolution of the late twentieth century. This is while educational and training programs, large scale testbeds, and skilled workforces are in short supply and are expected to remain a major challenge to innovation, development and adoption over the next decade.

The concept of cyber-physical systems (CPS) was first established over a decade ago as a next technological step in engineering. As such its evolution has arisen from multiple foundations resulting in a family of systems that have the potential to provide remarkable solution for traditional, contemporary and emerging areas of societal need.

A CPS essentially involves the integration of two subsystems: a computationally based subsystem involving sensors, communication infrastructure and computational elements and a physical one with components particular to the application context. For example, in power grid applications this would include electricity generation and transmission infrastructure, in transportation systems this could include power train and chassis control, in robotics applications it would include the motor units, gear box and arms. The cyber component represents, in some sense, the overall "central nervous system" of the CPS. It provides the "smarts" of the system essentially enhancing the operation of the physical system. A simple design mantra

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for CPS can be stated as *knowledge is power*. What distinguishes CPS is that the integration between the cyber and physical is considered tight. That is, these subsystems must intelligently work together and coordinate seamlessly.

This tight integration is aimed to facilitate attractive system properties including adaptability, autonomy, efficiency, functionality, reliability, safety and usability. Depending on the application and resources available, these properties are prioritized to different degrees. For example, in critical infrastructure, reliability and safety are of primary importance and in manufacturing, functionality may be a significant concern.

Figure 1.1 illustrates how the coupling of the cyber and physical components typically occur. The physical subsystem is comprised of components that are naturally linked physically. Often, they may be considered legacy system components of the original physical system prior to "cyber-enablement." The cyber subsystem is comprised of elements that are connected as well for the purpose of information flow. These could be through physical means such as two sensors connected through a physical communication wire or virtually through a wireless channel. In the physical and cyber subsystems, they are each individually coupled functionally as illustrated; typically, a graph-based model is effective in representing the connectivity.

The integration of the cyber and physical elements occurs at the *cyber-physical bridge*. Here, the physical-to-cyber link occurs at the sensors that convert observable and measurable physical quantities to data. The cyber-to-physical link occurs at the interface of actuation whereby information is processed to come up with decisions used to make physical change in the physical system. For example, this could be a storage device in a power system that employs information to decide if power should be absorbed or emitted for power grid stabilization. CPS can vary significantly in scale. The emerging trend is in the development of large-scale distributed networked systems.

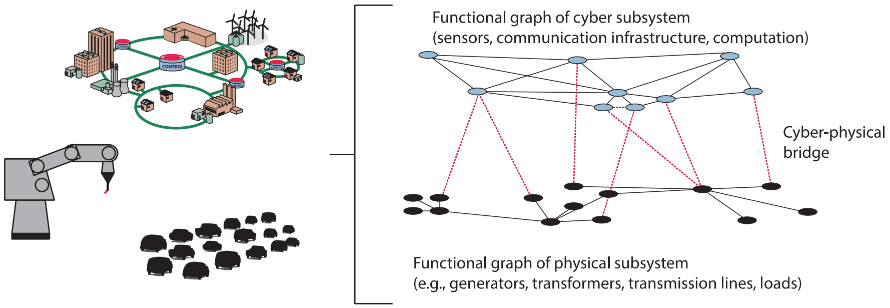

Fig. 1.1 Cyber-physical system description

1.2 Cyber-Physical Systems Characteristics

CPS are safe and interoperable smart networked systems with distributed and deeply integrated cyber and physical components including sensing, control, processing and computing, communication and actuating elements that are capable of interacting with physical world and human users in real-time [NSF (2013); Schätz et al. (2015); NIST (2013a)]. A cyber-physical system can be a small and local system such as a building management system or a highly connected, complex, and large system integrated over several domains such as a city-scale autonomous transportation system or a smart electric grid which is spanned over a continent.

The sensing, actuating and human-interactive features of CPS in combination with their highly distributed and networked intelligence and computational power have the potential to significantly increase efficiency, flexibility, and autonomy while improving the situational awareness, robustness and resiliency of the present systems that are loosely coupled or manually operated [National Academies of Sciences, Engineering, and Medicine (2016)]. Yet, safety, security and reliability remains the top priority for CPS given the integral role that CPS plays in mission oriented and safety-critical systems like transportation systems and healthcare. CPS are closely related to other fields including embedded systems, robotics, Internet-of-things, and big data [National Academies of Sciences, Engineering, and Medicine (2016)].

Embedded Systems: The field of embedded systems is focused on the integration of cyber elements such as processors and software to purely electrical and mechanical systems to perform a specific task. The generalization of the concept of embedded systems to perform multi-tasking in real-time through the integration of distributed sensing, computation, control, and actuation over a communication network has led to the notion of CPS.

Robotics: The field of robotics is focused on the seamless integration of sensors, actuators, processors and control to perform a task autonomously or semi-autonomously. Although similar elements are present in both fields of robotics and CPS, the strong emphasis on distributed sensing, processing, control, actuation and networking is a distinguishing feature of a cyber-physical system.

Internet-of-things: Internet-of-things is focused on dynamic communication network infrastructure with standard interoperable protocols that autonomously communicate data amongst entities with well-defined and unique identifiers. These entities include physical equipment, virtual elements, computing devices and human users. In contrast to CPS, the concept of Internet-of-things does not place emphasis on the aspects of control or regulation, computational power and human-machine interaction.

Big data: The field of big data is focused on the systematic analysis, storage, and visualization of a large volume of data. Although the field of big data has applications in CPS, its focus is limited in comparison to CPS and does not address the limitations of CPS for data management and analysis.

1.3 Drivers for the Development of Cyber-Physical Systems

The main drivers for the development of CPS include security, economic competitiveness, societal needs and technical drivers [NIST (2013b)]. As the cost of sensing, control, processing and computing, communication and information technologies continue to drop and the levels of connectivity between systems continue to grow, the vulnerability of systems and the number of attacks and intrusions is expected to grow. Thus, it is expected that the expense of security consume significant share of expenditures in all sectors. In this environment, security will be the main motivation for the development and adoption of trustworthy, cyber-resilient, safe and reliable CPS.

The higher levels of consumer demand and the need for improved efficiency will generate an economic competitive driving force for innovation, development, and adoption of CPS. As the interoperability, modularity and high functionality of CPS combined with their safety, security and reliability advances and become more evident, their application in all sectors become more prevalent. Deregulation of electricity markets is a prime example where the need for higher levels of efficiency and competitiveness became a motivation for innovation and development of smart grid concept. Growing competitiveness of businesses in combination with the increased deployment of cost-effective sensing, processing, information and communication technologies is also a major incentive for pushing forward the innovation in CPS and shaping the future deployment and adoption of these systems in all sectors.

The endeavor for improving life quality and standard is another driving force for innovation and development of CPS. CPS play a key role in domains that involve human interaction and cover both societal and technical aspects. Moreover, cyber-physical technologies are capable of performing tasks that are either dangerous or difficult for humans and significantly reduce accidents caused by human error. For example, it is expected that the application of CPS grow dramatically in sectors like transportation, healthcare, and mining as they become more affordable.

The need for improved reliability, reduced installation costs, automation, seamless human-machine interaction and higher levels of connectivity and remote access in industry is another reason for innovation and development of CPS. CPS provides an advanced platform for flexible, adaptive and autonomous systems that are compatible with heterogonous systems containing legacy systems and human users.

1.4 Applications of Cyber-Physical Systems

CPS are used for various applications in different sectors including manufacturing, transportation, energy, agriculture, smart buildings/structures, emergency response, defense and healthcare. This section briefly discusses the application of CPS in these sectors. A more detailed overview of CPS applications in industries other than the built environment will be provided in Chap. 3.

Manufacturing: CPS will play a vital role in keeping up with fast-changing and complex needs of consumers by providing smart, flexible and networked manufacturing production lines. The smartness, flexibility and connectivity of CPS also reduces the lead times required for changing the size and production level of manufacturing systems. In the present global market place, it is imperative for manufacturing industries to rely on CPS in order to maintain their economic competitiveness [Monostori et al. (2016)].

Transportation: CPS can significantly reduce air and vehicle traffic and improve public transportation system by introducing smarter traffic control mechanisms and intelligent/autonomous transportation systems. Moreover, CPS can eliminate accidents caused by human error by improving the autonomy and intelligence of transportation systems [Deka et al. (2018)].

Energy: CPS play a vital role in realizing smart energy systems for a sustainable future. CPS with their connectivity, smartness, interoperability, flexibility and self-healing properties can provide a platform to improve efficiency, sustainability and resiliency in energy sector. Moreover, the interdependency of different energy sectors like gas and electricity on other related infrastructures such as transportation, water and telecommunications highlights the critical role that CPS can play in energy security. For example, the massive integration of renewable energy resources like wind and solar, electrification of road transportation, and continuously aging power system legacy assets coupled with more frequent natural disasters and possibility of cyber-physical attacks demand higher levels of situational awareness, autonomy, adaptability, flexibility, resiliency and self-healing properties in the electric energy systems which is achievable through CPS [Kezunovic et al. (2016)].

Agriculture: Climate change and higher needs for agricultural products due to growing population is expected to become a major challenge in the following decades. CPS will play a key role in addressing the pressing need for smarter, more efficient and sustainable supply chain of agricultural products while providing opportunities for higher levels of productivity.

Smart buildings/structures: Building management systems are becoming smarter and connected with external infrastructures such as first responders and law enforcement. Moreover, structures like bridges, highways and tunnels use different sensors to improve sustainability and resiliency as well as safety and reliability. CPS in smart buildings can significantly improve energy efficiency by measuring different quantities like temperature, occupancy, light intensity and humidity in real-time and adjusting energy consumption. Moreover, CPS can play a vital role in improving the security of building management systems [Schmidt and Ahlund (2018)].

Emergency Response: Climate change has already resulted in more frequent natural disasters such as hurricanes, tornados and wild fires. CPS can significantly improve situational awareness and support first responders during natural disasters through their sensor networks, surveillance systems, intelligence, automation and robotics [Zander et al. (2015)].

Defense: Defense systems are becoming more reliant on complex, adaptable and autonomous CPS such as unmanned aerial vehicles, robotics and surveillance systems for meeting the military and national defense needs to reduce the human involvement. Moreover, cyberwarfares which rely on CPS has become an important part of offensive and defensive operations.

Healthcare: CPS are becoming prevalent in medical devices like artificial pancreas since they can autonomously monitor and react to abnormal body conditions. Moreover, CPS are expected to play a vital role in providing supporting systems for elderly people, people with disabilities and patients that need 24/7 care [NITRD (2009)].

1.5 Evolution of Cyber-Physical Systems

The transformation of purely electrical and/or mechanical engineering systems with physical implementation of sensing, actuating, control, and decision making to physical systems with cyber elements in the form of sensors, processors and software resulted in the emergence of embedded systems which are designed for a specific purpose. Afterwards, the need for the development of networked and multi-purpose monitoring, surveillance, and control systems in various applications including defense, energy systems, transportation systems, healthcare, and first responders resulted in the emergence of sensor networks and secure networked control systems. The notion of CPS is then developed and emerged out of the generalization of the concept of embedded systems and by parallel contributions from the fields of sensor networks, embedded systems and secure networked control systems. CPS are realized by the seamless and secure integration of spatially distributed and networked sensors, actuators, computing devices, and feedback control systems that are interacting with each other, the physical world and human users over a communication network in real-time.

1.5.1 Foundations of Cyber-Physical Systems

Sensor Networks Sensors connect the physical world with the cyber world by converting the real-world phenomena into signals that can be processed, stored, visualized and acted upon in the cyber world. Therefore, they can be integrated into many devices and used in numerous applications. The rapid advancements in the design of low-power, and inexpensive sensors have contributed to the emergence of distributed sensor networks (DSNs) over the past decade.

DSNs are comprised of low-cost unattended groups of densely placed sensor “nodes” that observe, communicate (often using wireless means), and coordinate to collectively achieve high-level inference tasks. DSNs represent a conceptual shift in the way humans and machines monitor, and interact with the physical environment and have found a wide range of applications including surveillance, safety, condition monitoring, and process automation. For example, DSNs can be employed to monitor and protect civil infrastructure such as bridges and tunnels by collecting structural health information using spatially distributed vibration sensors.

The spatially distributed and collaborative nature of DSNs introduces several challenges and benefits. The challenges facing the development and adoption of DSNs include safety, security, real-time performance and energy consumption as well as availability, reliability and robustness in harsh environments. The major benefits associated with DSNs include cost effectiveness, flexibility, efficiency, autonomy, redundancy and distributed nature. The DSNs can be considered as the first building block of CPS which provides a cost-effective, flexible, and reliable platform for monitoring and interacting with physical world in real-time.

Embedded Systems Embedded systems can be broadly defined as devices that contain tightly coupled physical (mechanical and/or electrical) and cyber (processor and software) components to perform a specific task. Most of embedded systems operate in constrained environments and interact with physical world in real-time which imposes limitations on available resources like memory size, processing power and power consumption.

Embedded systems are present in almost all the devices around us like microwave oven, refrigerator, dishwasher, printers and even our watch just to name a few. In CPS, distributed embedded systems perform multiple tasks in a coordinated and collaborative way in real-time. Although embedded systems form the computational foundation for CPS, the need for distributed, coordinated and collaborative computations in real-time create challenges that are specific to CPS such as the need for asynchronous computational models. The challenges facing the transformation of embedded systems to CPS are discussed in the Section on distinguishing features of CPS.

Secure Networked Control Systems The rapid deployment of distributed sensors, actuators, communication networks and processors in control systems resulted in the emergence of networked control systems. Networked control systems are central or distributed control systems that exchange information with distributed sensors and actuators over communication networks. In comparison to traditional control systems, networked control systems provide several benefits including reduced costs, improved flexibility, reliability and interoperability. Yet, the uncertainty in the integrity of data received from distributed sensors and commands transmitted to actuators as well as the potential unavailability of communication networks introduces new challenges for the design of networked control systems. For example, the unavailability of the feedback loop signals due to communication channel loss may cause instability problems for control systems with drastic consequences.

The efforts to address these challenges resulted in the emergence of the secure networked control systems. The field of secure networked control systems is concerned with the design of control systems that can survive conditions where the availability and integrity of data is compromised [Cardenas (2008)]. The design of distributed, secure, robust, and fault-tolerant control systems form the foundation of secure networked control systems which are necessary for the development of CPS.

1.5.2 Principles of Cyber-Physical Systems

CPS consists of physical, cyber and control/decision making elements. The physical elements in CPS refer to the electrical and mechanical components as well as the physical world that CPS is interacting with in real-time. The physical elements follow the principles of the physical world which includes physics, mathematics and mathematical modeling, probability, statistics and stochastic processes, logic, linear algebra and analysis. The cyber elements in CPS refer to the software, data structures, databases and networks as well as the processors and computational devices. The cyber elements follow the principles of computer engineering and computer science which includes software programming, computational hardware, processors and embedded computation, and networking. The control/decision making elements refer to cyber and physical elements that process and monitor incoming information from sensors and commands the actuators to perform various tasks through feedback control loops. The control and decision making elements follow the principles of control theory, adaptive and robust control, distributed and fault-tolerant control, stability, optimization, hybrid systems, digital and real-time systems [National Academies of Sciences, Engineering, and Medicine (2016)].

1.5.3 Distinguishing Features of Cyber-Physical Systems

CPS are founded by bridging the cyber and physical elements including distributed sensing, communication, computing, control and actuation elements which are interacting with physical world and human users in real-time. Accordingly, CPS demand distinguishing features as follows [National Academies of Sciences, Engineering, and Medicine (2016)].

Advanced Computational Models and Concepts CPS rely on distributed sensor networks that provide variable number of inputs about changing physical environment and human user needs in real-time and demand adaptive control and decision making and variable number of outputs. This characteristic demands novel computational models that are different in two respects from classical computational models.

First, computational models with adaptive and variable number of inputs/outputs are essential for CPS. For example, consider time-varying number of electric vehicles at a charging station that should negotiate and decide how to charge/discharge their batteries depending on the need of their users and the availability of power from the electric grid. In this scenario, the electric vehicle charger receives input signals from various number of agents including the electric vehicle owner and should make correct decisions about charging/discharging of the battery. Another example is a set of autonomous vehicles that should change their speed depending on the traffic status and passenger needs. This is in complete contrast to the classical computational models where models are developed based on fixed and known number of inputs/outputs.

Second, distributed, and collaborative computational models are required that are coordinated in a synchronous or asynchronous fashion. In classical computational models, the computations are performed sequentially. In contrast, in CPS distributed and variable number of processors perform computations and communicate data collaboratively which can be coordinated in a synchronous or asynchronous fashion depending on the application. In synchronous computational models, the processors work in harmony and exchange messages in synchronized rounds. This is while, the processors in asynchronous computational models work at independent speeds and exchange messages on an as-needed basis. In both examples of electric vehicles and autonomous vehicles asynchronous computational models are required where each vehicle optimizes its objective and exchanges information with other vehicles on an as-needed basis.

Discrete and Continuous Mathematics and Modeling An important difference between CPS and classical systems is that both discrete and continuous mathematics and modeling are needed for CPS. Such systems which require both discrete and continuous modeling and mathematics are called hybrid systems. For instance, cyber elements in CPS follow event-driven models and discrete time mathematics while physical elements follow continuous time evolving models and continuous time mathematics. Thus, the knowledge about the integration of discrete and continuous models and mathematics are critical. This is while either continuous or discrete mathematics and modeling is used in classical systems. Smart grids are prime examples of CPS where communication networks and power systems constitute the cyber and physical elements which respectively function based on discrete and continuous modeling and mathematics.

Real-Time Computing for PhysicalWorld The real-time characteristic of CPS distinguishes them from conventional systems. In a real-time system the accuracy and correctness of the system behavior depends not only on the correctness and accuracy of the results, but also on the time instant at which these results are available to be applied. As such, specific operating systems, computing architectures, and programming languages are required with the ability to address the requirements of CPS for real-time computing. Moreover, sophisticated models should be developed with the ability to predict and consider time delays while performing real-time control and decision making. For example, autonomous vehicles need to recognize the boundaries of the road, distance from different objects and adjust the speed accordingly while taking into account the time delays for receiving and processing data from sensors, as well as necessary time for computations and communication of commands to actuators.

Interaction with Physical World Interactions of CPS with physical world imposes complex design constraints on all elements of these systems. For example, type of sensors, processors, control systems, communication networks, and actuators that can be used will be imposed by the characteristics of the physical world that CPS interacts with. Moreover, other factors such as memory size, processing power and power consumption as well as redundancy and fault tolerance of elements may become decisive depending on the physical world constraints and cause unpredictable failures. This feature highlights the need for various testbeds to examine the CPS design requirements in a safe and controlled environment which is discussed next.

Safety-Critical Applications Testing, validation and certification for systems and devices whose failure do not result in serious consequences are normally performed at the final stage before deployment. This is while most of CPS are safety-critical systems whose failure could result in loss of life, significant property damage or damage to the environment. Thus, their safety, reliability and security has higher priority over other objectives such as cost and performance. The safety-critical applications of CPS in sectors like healthcare, transportation, and defense demand novel testing, validation and certification procedures and testbeds from planning to deployment stage including design, assembly, implementation, and delivery stages.

Cross-Cutting Technologies CPS are underpinned by cross-cutting technologies that facilitate the following characteristics.

- Abstractions, modularity, and composability
- Standard and interoperable
- Adaptable and predictable
- Hierarchical and secure networked control and decision making
- Distributed sensing, communications, control and actuation
- Redundancy, resilience, survivability and self-healing properties
- Novel testing, validation, and certification mechanisms,
- Autonomy and human interaction
- Cybersecurity
- Resource constrained

1.6 Challenges and Opportunities

1.6.1 Challenges

The major challenges facing innovation, development and adoption of CPS can be classified into technological, educational and legal challenges [Schätz et al. (2015); National Academies of Sciences, Engineering, and Medicine (2016)].

Technological Challenges The technological challenges partly stem from the distinguishing features of CPS compared to classical systems. For example, technological advancements are required for the development of distributed, interoperable, autonomous and reliable systems that can protect safety, privacy, dependability and cybersecurity of CPS.

The development of interoperable systems with certain level of modularity, and composability that can be combined and integrated with legacy systems has been initiated in industry a decade ago but it is still at the embryonic stage in terms of deployment, testing and validation. In addition, the safety and reliability concerns are still the main barriers in front of the adoption of autonomous systems in different sectors. Considering the volume of data that will be generated, gathered and processed by CPS, development of various mechanisms for protecting the data privacy is another technological challenge that should be addressed properly. Lastly, cybersecurity is the most important technological challenge that must be addressed while designing CPS considering the critical role that they play in safety-critical systems like defense and transportation systems [Schätz et al. (2015)].

The other two contributing factors to technological challenges are the economic and scientific aspects. A good share of benefits associated with the CPS may not be quantifiable using classical business models since in many cases they only contribute to facilitating the processes or providing services rather than resulting in a product. Thus, new business models and cost/benetit analysis tools must be developed to justify the investment in CPS. Moreover, considering the transdisciplinary nature of the CPS, innovations in this field require scientific contributions from several domains. Therefore, a body of knowledge with suitable breadth and depth from several domains should be established for modeling, design and implementation of CPS. Finally, socio-technical aspect of CPS play a key role for their adoption in the society which demands a special attention.

Educational Challenges The skilled workforces, knowledgable experts, professionals and educational trainers with a deep understanding of CPS are in short supply and are expected to remain as a major challenge in front of innovation, development and adoption of CPS at least over the next decade. This is mainly because the field of CPS requires the integration of knowledge from multiple areas of engineering such as computer science, computing engineering, civil, mechanical or electrical engineering, systems engineering with a right balance between theory and practice. The breadth and depth of knowledge required for innovation and development of CPS makes the education in this field challenging. Therefore, new education/training systems should be designed and implemented based on the requirements of CPS [National Academies of Sciences, Engineering, and Medicine (2016)].

The lack of cyber-physical laboratories and testbeds in educational institutions and industry is another obstacle which hampers the provision of the required education/ training in the field of CPS. Individuals in the field of CPS need access to testbeds with different levels of complexity and integration of physical and cyber components so that they can develop relevant programming, simulation and experimentation skills.

Legal Challenges The application of the CPS in different sectors demands different legislations and regulations concerning the privacy of data, safety and security of systems and users, and liability as well as testing and certification of CPS. Moreover, considering that CPS may span over different states, provinces or even continents, new legal standards and terms may be needed to specifically address the needs of CPS [Schätz et al. (2015)].

1.6.2 Opportunities

CPS improve the efficiency, flexibility, reliability, autonomy and self-healing properties of systems while providing higher levels of situational awareness, robustness, resiliency and interoperability. Moreover, CPS enable better coordination, collaboration and control of large and complex systems. In addition, CPS provide opportunities for higher levels of connectivity and remote access. Finally, CPS provide numerous opportunities for skilled workforce to design, develop and deliver new devices, systems and services.

1.7 Conclusions

Cyber-physical systems are establishing themselves as a critical element of modern engineering systems design. Their multidisciplinary roots have helped to spur on interdisciplinary collaborations and results. Rich innovations exist at the intersection of traditionally siloed fields. As such CPS represent a paradigm shift in the way in which engineering systems are developed in terms of empirical and mathematical modelling, real-time computing, interaction with the physical world and safety. As their technologies become intrinsic to the operation of smart societies, it will become imperative to not only address technological challenges, but those related to shortage of an appropriately trained workforce.

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Chapter 2
Technology Requirements for CPS Implementation in Construction

Daniel Antonio Linares Garcia and Nazila Roofigari-Esfahan

2.1 Introduction

CPS implementation in the AEC industry can be challenging in many aspects. Having a clear understanding of the requirements, processes, and characteristics of CPS is needed to make informed decision-making, accurate budget and schedule estimations, and development of plans for proper CPS implementation in the industry. Significant CPS achievements, namely real-time monitoring, automation, digital twin representation, and bi-directionality can only be achieved through proper understanding of CPS at various levels. Understanding the technology requirements for CPS implementation can consequently help a company or the implementation team in assessing the preparedness of the organization for the acquisition of these technologies and formulation of a plan for implementation. This way, CPS can be gradually implemented, while systems in the organization adapt, technology champions are brought together, and training is undertaken in the early stages of implementation.

For this purpose, this chapter delves into the technological requirements for CPS implementation. The technology requirements are reviewed at three levels: device level, platform level, and system levels as illustrated in Fig. 2.1.

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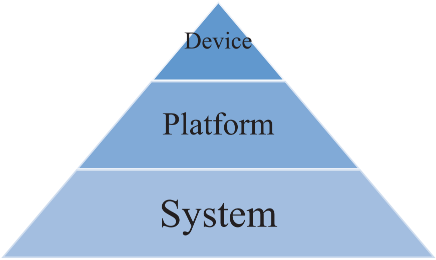

Fig. 2.1 Levels of analysis for technology requirements for CPS

2.2 Requirements of CPS at Devices Level

In this section, the CPS requirements at the device level are reviewed. Two categories of requirements are discussed: first are the general requirements that all the devices should abide, and then the specific requirements that are particular to a certain group of devices. For example, connectivity is required for all the devices to enable CPS, but sensing capabilities are not a requirement for all devices and is only expected of the sensors that should sense the physical system components for a specific application.

2.2.1 Connectivity

All devices in a CPS system are required to have connectivity capabilities to be able to send/receive data to/from other CPS components. As a general requirement for CPS, it is expected that all the components of the system communicate in some manner to support the necessary functions of the CPS. Connectivity can be achieved through wired or wireless network configurations. This capability depends on the limitations of the system, the platforms selected and the applied environment. In many circumstances, connectivity in CPS components becomes a secondary function, in addition to its primary function, because the information must flow from an end node device to a centralized node device. Still, communication capabilities are essential for all CPS devices.

Wired Wired connectivity for devices is one alternative commonly used in many industries. The simplicity of the wired devices and the ease of setups for wired platforms make it advantageous for many applications. In past decades, wired connectivity has been used to overcome the limitations present in wireless communications such as bandwidth and latency. Some applications of wired applications include surveillance, where quality videos have to be captured by image sensors (cameras) for surveillance analysis (Chandramohan and Christensen 2002). Setting a wired network usually involves a plug and connect of the wired elements, and no specialized knowledge and training is needed.

In multiple cases, wired connectivity also provides energy to devices, thus making wired systems more sustainable and reliable. However, wired connectivity is limited as it needs a built infrastructure to be used, which in specific conditions adds complexity to the setting and implementation of CPS, or simply, makes it impossible to accomplish. Besides, because of the same reason, wired systems are not readily adaptable and scalable. This is a limitation for constantly changing environments, such as those of construction projects. If a wired sensor system is in place, the network has to be set up at the beginning of the project and has to be continually adapted to accommodate the needs of the ever-changing construction site.

Wireless Wireless connectivity is becoming the de-facto alternative for modern CPS applications because of its advantages and because of the advancements in commercial wireless communications devices, platforms, and applications. Besides the capability to exchanging information contactlessly, wireless connectivity allows communication platforms to be more scalable, adaptable, secure, and more ubiquitous depending on the wireless technology platform selected. The different wireless platforms allow devices to communicate to multiple devices (i.e. Zigbee), closed networks (i.e. wireless sensor networks), and cloud platforms (i.e. Internet of Things) (Yue and He 2018). However, advanced knowledge is required in order to set wireless devices to work properly. In addition, wireless devices typically need to be powered by batteries which have to be regularly replaced or charged. Due to their adaptability, wireless systems are more applicable in construction sites in comparison to wired systems because devices only need to be repositioned and reconfigured, if required. Regarding scalability, wireless platforms scale better and depending on the technology used, wireless device nodes can be easily added and set. Technologies that support wireless connectivity at the device level are Bluetooth, WIFI, Cellular, UWB, Zigbee, etc.

2.2.2 Data Exchange

One of the essential characteristics of CPS is bi-directional data exchange between physical components and their cyber counterparts. However, bidirectionality among CPS devices is not always present at the device level. The reasons are that very often, CPS devices at the end nodes, such as sensors and actuators, are single-tasking components. This means that an end node can only receive data or send data. Figure 2.2 shows an example of data exchange for a CPS system to illustrate the unidirectional flow of information for the cases of sensors and actuators. In this case, sensors perceive and transfer data to the cyber space, and once the data is processed, the retrieved information is sent back to the physical world through actuators. On the other hand, a robot, as represented in Fig. 2.2, can be considered a multi-tasking device that is capable of bi-directional communication. Other examples that have bidirectional data exchange are human communication terminals (phones, computers), connected vehicles, and embedded electronic systems.

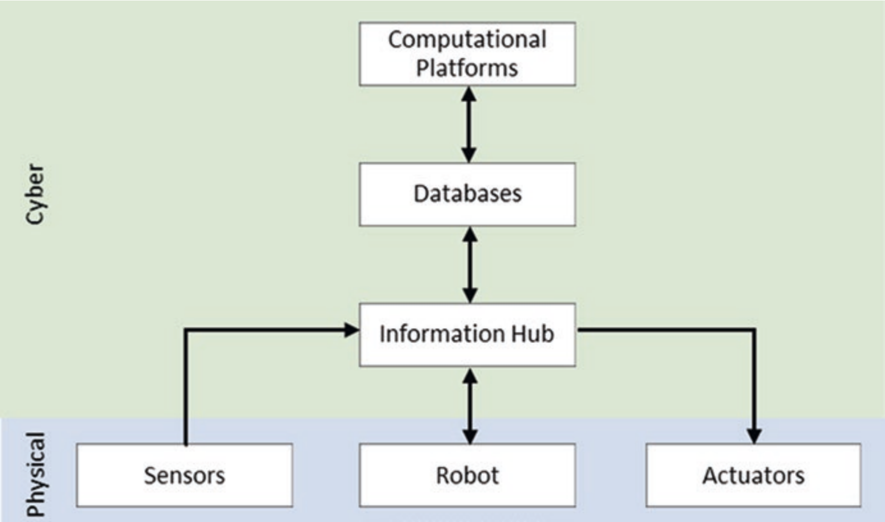

Fig. 2.2 Data exchange scheme example

Data exchange is supported by technologies such as wireless communication, relational databases, cloud computing, APIs, graphical user interfaces (GUIs), and devices such as smartphones, and smart handheld devices, among others.

2.2.3 *Identifiers*

A necessary requirement of CPS is defining a proper identifier for all physical components. Such identifiers help establish the proper link between the physical components and their cyber replicas. Identifiers help to define better management practices for implementation through correct identification schema establishment. These are defined as the continuous, unique, and coherent naming and/or coding of the elements for the goal of referencing or calling these elements in the processes of the system. In other words, each sensed physical element such as users, equipment, and tools/devices should have a unique identifier so any of these elements can be called up later without causing confusion among similar elements. Identifiers are a general requirement for the physical elements in CPS. This means that each sensor, device, network, and hardware have a unique identifier that the cyber side of the CPS system can interpret or address when needed without causing confusion. For example, identifiers schemas can provide status information about CPS components so changes in performance can be identified and solutions can be automatically deployed.

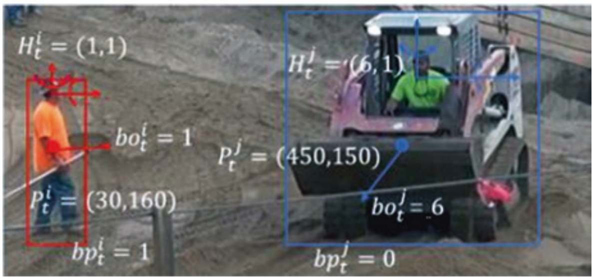

Fig. 2.3 Identification of resources interaction based on "attentional cues". Source: (Cai et al. 2019)

2.2.4 Human Interaction

Humans need to be considered in the loop when designing CPS platforms and selecting the system devices. This is due to the fact that (1) the human actors are considered an important component of the CPS that needs to be represented digitally in the cyber side of a CPS, and (2) some CPS components are prone to have interaction with humans. As such, human interaction capability is a requirement for the CPS components that ought to interact with humans. This plays a more important role in less automated industries such as AEC where many tasks are conducted manually by workers, compared to more automated industries such as manufacturing.

New technologies are being adopted in the CPS-based approaches in the AEC industry to address the these needs, i.e. track, monitor and predict human behavior and their interaction with surroundings CPS elements including the environment, equipment, tools, e.g. (Cai et al. 2019), and improve human interaction and usability of the system devices (Fig. 2.3). For instance, exoskeletons are being developed not only to monitor and improve humans physical capabilities but also to support human health in activities that pose a treat to human health or may cause chronical suffering. These technologies have to be selected to comply with the requirements to provide safety, keep personal and organizational privacy, and make devices and interfaces easy to use for human users. These characteristics have to be considered in the selection of CPS components and devices without compromising the intended function of the system. Technologies and devices the support human interaction include computer vision, exoskeletons, temperature sensors, thermal sensors, wearables, GUIs, Artificial Intelligence, cameras, robots, etc.

2.3 Requirements of CPS at the Platform Level

Platforms in CPS refers to the set of physical or cyber subsystems that enable the interaction between the physical and the cyber components of the system. Physical platforms include electronic platforms such as wireless sensor networks similar to

ZigBee, IoTs, and Wi-Fi, or cyber platforms such as the internet, BIM or a cloud computing platform. Identifying the appropriate platform to implement will help guarantee the proper functioning and flow of information in the aimed CPS and facilitate the integration of the platforms that are already in place in the industry or the organization. The main requirements in the selection of the appropriate platforms are interoperability, connectivity, BIM integration, and privacy and cyber-security.

2.3.1 Inter-Platform Interoperability

Currently, there is no unified CPS platform that integrates all the required components for proper application in the construction industry. Therefore, current CPSs use multiple physical and cyber platforms that must interact with each other while creating heterogeneous and massive amounts of shared information. Some of these platforms are inherently accessible because of their characteristics, but others do not provide seamless access and are not open to other platforms unless additional procedures are performed. One example is the internet as a cyber platform that is easily accessible to other platforms; on the other hand, platforms such as software applications are not easily accessible because of the proprietary of the software and the inability of the software to be bi-directionally connected to other platforms. Therefore, inter-platform interoperability entails a devising exercise of connecting not readily inter-operable platforms by computational means such as parsing and querying information in databases, accessing platforms through APIs, transferring information to open standards, and using relational databases. However, following those procedures often provoke information to be lost and the quality of the information to be compromised. In addition, the transitioning of information between platforms will be slower or even halted when information from closed platforms have to be converted to be made accessible. As such, the interoperability of CPS platforms remains one of the biggest challenges to solve for the application of CPS in many industries including the AEC industry.

Research in this area has demonstrated that in addition to technical challenges, the fundamentals regarding the understanding of CPS need to be re-assessed. Research also suggests that conflicting requirements in CPS are also an issue and make inter-operability an even more complex problem (Heiss et al. 2015). In other words, among the different requirements for CPS, some requirements are mutually conflicting; e.g. scalability and, reliability and predictability are also desired requirements of CPSs; however, when a CPS becomes more scalable, the predictability and reliability of the system will be compromised. The intersection of these conflicting characteristics, identified by Heiss et al. (2015), can lead to potential innovations in CPS development, if solved (see Fig. 2.4).

García et al. (2014) noted that the use of low-cost open platforms presents opportunities for experimentation, at least for hardware CPS applications. However, most of the industrial CPSs have to be implemented over an already existing platform

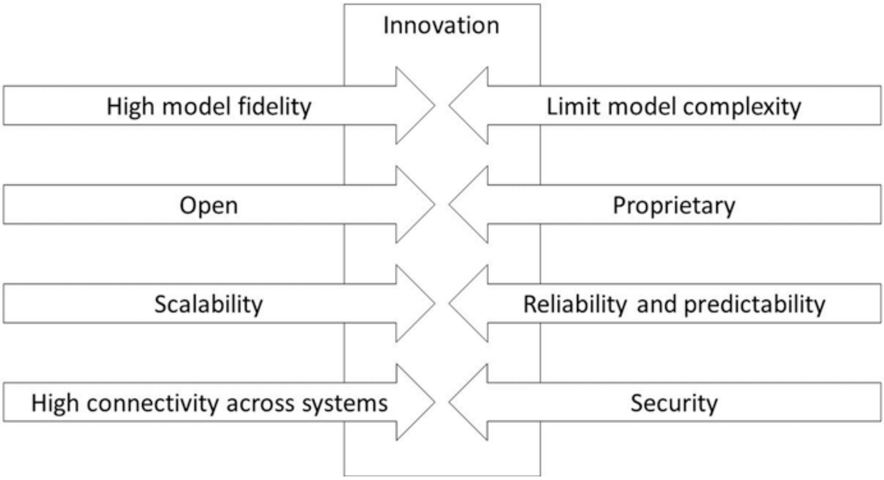

Fig. 2.4 Contradicting requirements and challenges for CPS. Source: Adapted from Heiss et al. (2015)

provided by a vendor; i.e. closed platform. Moreover, open standards have shown to be more practical than proprietary standards because these closed platforms impose additional challenges such as costs and training.

Technological platforms that support platform interoperability are Applications Programming Interfaces (APIs), big data, data analytics, cloud computing, databases, document management systems, and relational databases.

2.3.2 Connectivity

In addition to the connectivity requirements at the device level as mentioned earlier, additional requirements regarding the connectivity of CPS at the platform level have to be considered. To this end, further consideration of the way devices are connected (wired or wireless) and a revision of the integration among different communicating platforms to define a unified data exchange schema at platform level is needed. The requirements of connectivity at the platform level should be determined in a way to be compliant with other requirements such as reliability, cost, and interoperability.

Hybrid platforms that combine wired and wireless connectivity are a viable solution in various circumstances and are a typical option for CPS applications in the construction industry. Hybrid platforms have been developed by academia and industry to overcome the limitations of both systems and to bolster their advantages as a connected system. Hybrid wired and wireless solutions have notable advantages and disadvantages. Proprietary solutions from technology vendors are available for both wired and wireless connected platforms, e.g. wired sensor networks for structural health monitoring of buildings, wireless IoT networks for smart home automation based on Zigbee, etc. Coupling these available solutions will lead to improved accuracy and scalability, but at the same time, will increase the complexity of developing the system due to the fusion of the data generated. As such, establishing a proper connectivity platform is a unique task requiring a detailed study of the requirements of the system, and the proper system components.

One example of a hybrid connectivity platform is shown in Fig. 2.5, where a leveled sensor network is created as clusters of networks that communicate to a gateway, and at the same time, communicate with each other and transfer data to information hubs. Vivi et al. (2019) used this approach for a campus building sensor network using a combination of wired sensors that communicate wirelessly (infrared) to a gateway, and this gateway connects directly to a server to process, store, and transfer information. Some of the advantages of such systems are that the sensors can be more straightforward as their communication capabilities are directed towards one device (the gateway). In this case, the gateway may have more complex communication embedded systems. Other advantages are adaptability and scalability due to the ease of adding individual sensors or a cluster of sensors. Technologies

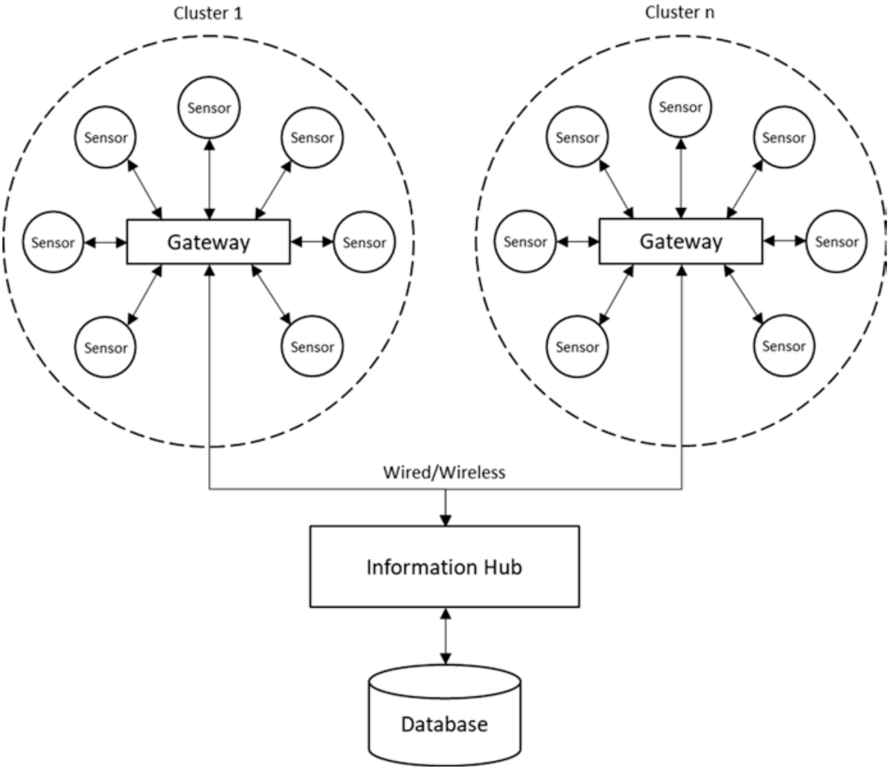

Fig. 2.5 Hybrid platform example. Source: Adapted from Vivi et al. (2019)

that support hybrid connectivity at the platform level include cellular, Wi-Fi, wireless sensor networks, ZigBee, blockchain, Bluetooth, IoTs, internet, and others.

2.3.3 BIM Integration

In the construction industry, BIM is the vessel to integrate the cyber applications, the building design, and the physical construction processes in AEC focused CPS applications. Because of this, the integration of BIM with other systems at the platform level is critical to sustaining centralized common data environments. The integration of BIM with the other requirements at the platform level assures that the building information sources are updated, transferred, and managed appropriately between the stakeholders. However, similar to the issue of inter-platform interoperability, full integration BIM in a CPS-based construction industry is challenging.

BIM-CPS interoperable solutions have been proposed to ease BIM integration to enable a bi-directional flow of information in CPS for the AEC industry. Interoperable architectures were provided that explain data flow scenarios to exchange information among IoT platforms and BIM databases, e.g. Tang et al. (2019). Their considerations include the use of open standards for building data, the use of relational databases, APIs, and parsing and processing data in secondary SQL databases. The diagram shown in Fig. 2.6 presents the sensor data in form of time-based data series on the right side, and how this information is transferred to the BIM or building context data through integrative methods, e.g. SQL querying, relational databases, and building context data from IFC, on the left side. Figure 2.6 is only one of the alternatives for interoperability between sensory data and BIM among others proposed by Tang et al. (2019). Other approaches for integrating data from BIM to

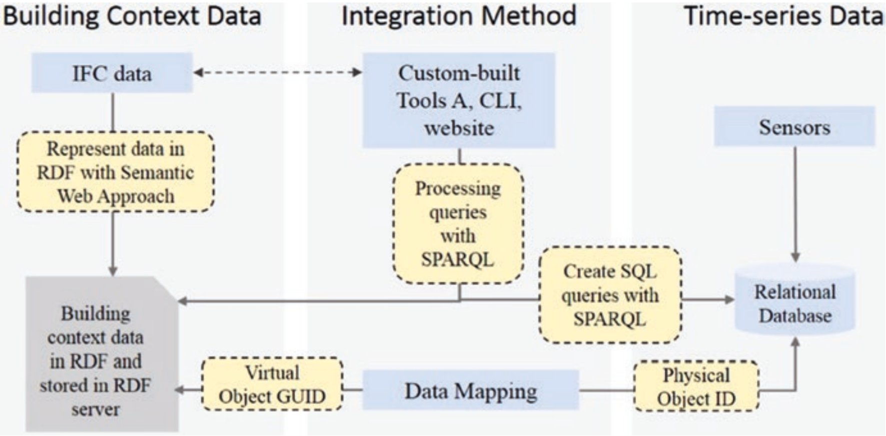

Fig. 2.6 Unidirectional interoperability schema between sensor data and BIM. Source: (Tang et al. 2019)

sensors are also being researched, however, the full integration and bidirectionality requirements still remain in the infancy stage of development and are not well developed for practical applications in the industry.

Technologies/concepts that support BIM integration at the platform level are digital twin, 4D/5D, cloud computing, databases, relational databases, document management systems, and mobile apps.

2.3.4 Privacy and Cyber-Security

CPS security and privacy have been identified to be a future frontier of concern for technology and a field that needs to be stimulated and matured in all industries, including AEC (Thomas et al. 2015). The transfer of information from people and organizations becomes a security concern when there is a risk that this information is to be accessed by outsiders, including automatic systems. According to Ashibani and Mahmoud (2017), security on sensor networks must be considered in the context of information security and control security. Information security is about unauthorized access to retrieve and store sensitive data that may be unproperly used. Control security is the security risks that may happen when one device or system, is controlled by someone not authorized, also known as hacking.

Similar to the issue of security on sensors networks, privacy issues can arise in these kinds of settings. These concerns are exacerbated when the sensed data include personal information, e.g. surveillance data such as imagery and location awareness of individuals, or objects that violate individuals' right for privacy. Therefore, privacy should be addressed at the root of the issue, having a system that provides transparency to the users (Chow 2017).

Other security threats have been identified by Jain et al. (2012). These treats put the performance of the CPS system or the integrity of the data transfer at risk. These threats are as follow:

- Denial of Service(DoS) is a type of cyber attack that overloads a cyber system with multiple requests for service which causes the victim cyber element to collapse or underperform because of overwhelming demand. Provoking a component of the system to collapse creates a bottleneck that affects the whole CPS at the system level or the platform level.
- Sybil attack is a particular type of attack that affects decentralized or peer-to-peer systems such as those of some CPS platforms. In a Sybil attack, multiple fake entities in a system gain control over real system entities to destabilize the whole system schema.
- A Blackhole/Sinkhole attack happens when an infected node in a system redirects data traffic through the blackholed node in order to gain control over the data packets redirected.
- A Wormhole attack happens when an attacker records the data at selected locations in the network and sends this information to another location

Below is a list of the security solutions for sensor networks (Jain et al. (2012)) and that can be applied to CPS in the AEC industry:

Encryption Because of the amount of information that runs publicly and in open channels, encryption is a need for in CPS in AEC. Encryption helps to transfer data over these networks more securely by hiding the original data and avoid sensitive information to be observed by outsiders or malicious attackers. Within the context of encryption, shared keys are a technique to provide the right keys to decipher encrypted information to the target people. In this way, information between sensors, stakeholders, and systems will have the right keys to decipher encrypted data.

Communication Under Security CPS platforms and devices may need to cooperate automatically within secured networks. Therefore, a group of devices needs to be programmed to communicate effectively despite the security measures placed in the system.

Data Aggregation Data aggregation refers to when multiple CPS entities collect information within an information hub, and then this collected information is transferred inside or outside of the system. A security problem is that the aggregated data is desirable to attackers; therefore, the securing of aggregated data is especially vital in CPS networks.

2.4 Requirements of CPS at System Level

The technological requirements of CPS at the system level, define the basis for what the system does to operate and what are the ultimate objectives that the system in place have to achieve. The requirements at the system level seek to support the requirements at the platform and device level. The requirements for the system are listed in the rest of this section based on Etxeberria-Agiriano et al. (2012).

2.4.1 Autonomy

The autonomy of CPS is an idealization by researchers, but in reality still cannot be achieved in most cases including the AEC industry. So, human feedback is still essential in the currently established CPS. In other words, the application of CPS that autonomously process raw data and provide valuable insight to humans is desired and is being one of the research focusses in the last years. However, the autonomy of CPS subsystems (and not the whole CPS) is more attainable and expected within a CPS. For now, the autonomous processing of raw data into information insights is one of the most common features that current CPSs need to address. Higher levels of automation, such as automatic updates of project information or documentation, have been proposed but remain a niche in the construction industry.

2.4.2 Real-Time

Real-time applications of CPS in the construction industry tend to be especially useful for multiple applications. The approach for a real-time application can be based on the demands of the sensed elements, the capacity of the system, or time and event constraints. However, CPS systems in the AEC industry can leverage the use of less stringent system behavior by prioritizing predictable behaviors under relevant events (soft real-time) rather than predicting behaviors at every specific moment even when nothing is changing the system conditions (hard real-time). In other words, the dependability of a CPS system in the AEC can be enough if the behavior of the system is consistent under important events or time frames, rather than recording every time period the system, even when the system is idle. Reasons to prefer soft real-time over hard real-time include the additional expenditure on resources, increased resource capacities, and overload of information.

2.4.3 Reliability

After an automated application is established, organizations tend to rely on the system and expect these systems to work flawlessly and achieve the intended goals. The failure or poor performance of a component of a CPS may have consequences that could make the whole system collapse. In the case a system element collapses, finding the faulty element may not be an easy task depending on the complexity of the system and operations can be halted for indefinite periods of time while the faulty component is found and fixed. For these and other reasons, malfunctions in CPS need to be avoided at all costs and performance indexes must be placed. As such, the reliability of CPS need to be ascertained through various approaches including certifications, regulations and ensuring abidance with the requirements of the standards.

Another approach is to make CPS systems more resilient. The resilience of CPS can be achieved by self-monitoring, self-repair or provide humans feedback about reliability issues in post-facto or by a predictive approach. Besides, CPS subsystem must be self-reliant. This happens when provisions are made to make a system capable of performing the desired task even though a component or a subsystem fails to support the system. Some ways to do this is by providing a backup of essential CPS components and subsystems and rely on processing capabilities within the system rather than possessing only cloud processing. For example, in the case of an autonomous safety system for construction equipment, processing capabilities in the construction equipment itself may make the system more reliant than processing on the cloud because connectivity can fail, leaving the equipment operator exposed to safety hazards. Likewise, in CPS applications that impact the health and safety of workers, CPS needs to be essentially reliable to ensure the safety conditions for these human workers.

Finally, the reliability of CPS systems can be supported by adding transparency to the systems. In other words, the status of the system must be easily communicated, especially when the system is faulty or simply not in use; e.g. in the previous example about the autonomous safety for the construction equipment, a status alert should be included to show when the system is working, when the system is faulty, or not in use while the equipment is running. This may help the operator to decide to stop operations or to be more cautious because of the supporting system is in idle or is in a faulty status.

2.4.4 Time Management

The information managed in CPS relates to physical occurrences of events at specific locations and times. The temporal dimension of the information used in CPS becomes critical when it is managed and processed by heterogeneous devices and platforms. Moreover, historical analysis of information of the collected information is an important requirement in the construction industry to address disputes and issues.

2.4.5 Integration

Current CPSs are a mixture of different devices and platforms that must work together in order to accomplish their intended goals. Interoperability is a challenge in CPS as the capacity of these devices and systems to efficiently exchange and use information is different and in most cases incompatible. As a result, integration and fusion of the multiple types of data collected from different sources is an important issue that needs to be addressed. Therefore, solving the interoperability challenges between platforms, devices, and systems will leave systems that have higher integration that potentially can better accomplish the goals of CPS.

For this purpose, architectures and frameworks for data exchange have been developed to define protocols for information processing in a network of CPS devices. Examples of these architecture include: frameworks for big data in construction (Han and Wang 2018), framework of CPS in the construction industry (Correa 2018), knowledge management architecture for CPS decision-making in construction (Fang et al. 2018), safety in construction based on autonomous systems (Kanan et al. 2018), and framework for BIM and IoT devices integration (Tang et al. 2019), to name a few.

A more fundamental approach to integrating technologies for CPS is to define regulations and standards for proper CPS functioning. Efforts to develop standards from regulators, e.g. the NIST framework for CPS (Griffor et al. 2017), are being undertaken, yet are in the nascent stages of development. Furthermore, research on evaluating CPS architectures from the standards perspective has been developed by some researchers, but still are no addressing the issue in full potential, e.g. research efforts made by Ahmadi et al. (2017), and Dave et al. (2018).

2.4.6 Resources Optimization

The devices that serve as vessels for CPS implementation are somewhat limited to their specific capabilities. Some of these devices have limitations on processing power, storage options, connectivity, and energy consumption. As such, the CPS architecture and the devices used must be tailored to the specific needs of the problem sought to be solved. These limitations also exist for economic reasons as CPS, as a network of devices, can include hundreds or thousands of network nodes that need to do processing, storage, and/or communication. Therefore, the cost of one device can be exponentially augmented and become an economic barrier for the developer. Also, a fixed limitation may exist depending on the platforms and devices used. For example, a System on Chips (SoC) solution may be limited in processing capabilities because of the platform itself but still accomplish the connectivity requirements for a CPS implementation. Potential solutions include developing information hubs where processing and storing of information is less restrictive and connecting the nodes to these hubs.

2.4.7 Adaptability

The construction industry is a good example where the adaptability of CPS must be a decisive factor for implementation. The capacity for a CPS to be reconfigurable and have multiple organizational alternatives is vital to enable adoption to changing environments such as those of construction sites. An ideal case is when the CPS self-adapt to the conditions and requirements and needs of the system. Self-adaptability is a topic of interest in other industries including the manufacturing industry where research is undertaken to further implement this approach (Zhou et al. 2018).

Also pressing is the need for CPS to be scalable. This means that an updated CPS system that changes in size (bigger or smaller) can easily be implemented seamlessly based on the base CPS architecture (Vivi et al. (2019).

2.5 Conclusions

Delineating the technological requirements for the implementation of CPS in a construction setting is a complex process. Multiple factors have to be taken in consideration for a CPS that is aligned with the objectives of the organization and the intended use. For this purpose, these requirements are evaluated in this document from three levels that cover all the factors from micro to macro perspective. This perspective may help a CPS implementation team to take a holistic review of the devices and platform alternatives that together define the characteristics of the system.

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Chapter 3
CPS in Other Industries

Daniel Antonio Linares Garcia and Nazila Roofigari-Esfahan

3.1 Introduction

Across many industries, CPS is envisioned to offer a unified, integrated system to manage information, system elements, and processes that achieve a varied number of goals. As the concept of CPS pertains to bidirectionality, data and information flow play an essential role in sensing the physical assets and the related processes and creating a virtual representation of the physical system, referred as digital twin. Autonomous management decisions are then transferred to the physical asset in order to actuate or modify processes pertained to the asset actions. However, across different industries, a unified concept of CPS does not exist, and multiple CPS definitions have been developed for different goals in different industries. CPS use in each industry is fragmented, and the independent systems developed for different functions may not communicate with each other or with those of other industries.

The CPS potential to revolutionize the interactions of complex applications and systems for the benefit of humanity is latent. Spearhead developments and improvements of CPS have been developed in different industries. In this chapter, the applications of CPS in other industry sectors, including manufacturing, healthcare, transportation, aviation, agriculture, energy distribution, etc. are discussed.

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3.2 CPS in the Manufacturing Industry

The manufacturing industry is known to be a pioneer in the implementation of advanced technology, ahead of other industries. The process optimizations and resources management in the manufacturing industry has been one of the most beneficial areas of application of CPS in this industry. These benefits have justified the investment to update the existing infrastructure to an updated CPS-enabled infrastructure. Companies such as IBM, GE, and Cisco are among the companies that have made progress towards CPS-enabled infrastructure. A challenge faced to update manufacturing to CPS-enabled approaches is that in addition to an updated infrastructure, information and software systems also need to be updated and integrated into such manufacturing systems (Kim and Park 2017).

Other applications of CPS in manufacturing focus on real-time tracking of resources and processes through bi-directional sensing and communication, to optimize manufacturing processes. Real-time tracking helps to achieve digital twin applications for the manufacturing processes that accordingly enhances manufacturing management. Frontoni et al. (2018) used digital twin for real-time tracking of manufacturing processes and at the same time visualizing these processes through virtual reality. Figure 3.1 shows the web interface visualization for equipment operation by Frontoni et al. (2018).

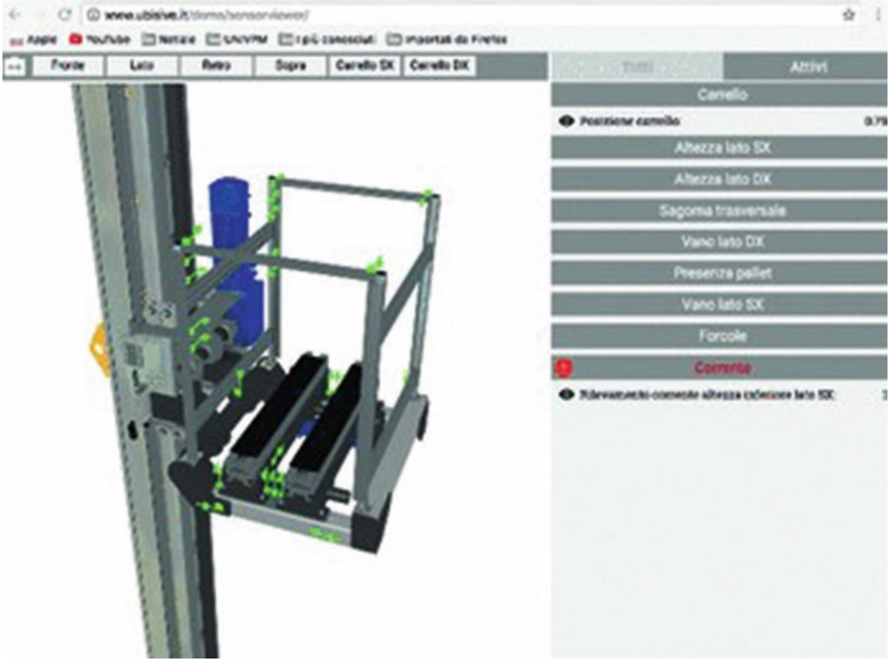

Fig. 3.1 Visualization of CPS process for manufacturing using a web interface. Source: (Frontoni et al. 2018)

Within the concept of automation and optimization, new schemas are being developed to enhance manufacturing processes. These new schemas include developing the processes required to detect the varying flow of demand in the manufacturing processes and make the needed adjustments in the production line to achieve production goals. Some schemas go beyond the optimization of the production line and employ CPS based approaches for redistribution of the manufacturing facility spaces. For example, Brusaferri et al. (2014) developed a CPS-based architecture to autonomously change the manufacturing space layout to accommodate varying demand for manufacturing products. Similarly, other studies focused on detecting faulty manufacturing or CPS element, so the CPS environment reconfigures itself to compensate for the lack of progress by the faulty element (Hyun-Jun et al. 2018).

Equipment and system health monitoring is another application in CPS-enabled manufacturing. The application of CPS in the manufacturing processes allows monitoring sub-optimal performance by equipment or systems. With CPS, sub-optimal performance can be traced to the root of the problem according to the multiple sensors data and the analysis of this data. The maintenance forecast is the next step to health monitoring systems for manufacturing in CPS environments. By prior identification of system problems, manufacturing systems can also become more efficient in the identification of recurrent system failures (Gao et al. 2019).

A critical factor to be considered in applying CPS in manufacturing systems is the human factor and how it affects CPS processes. As noted by Fantini et al. (2016), the human factor is still unclear within the CPS systems. In this study, types of human interventions were evaluated to define their effect on CPS processes and the skills humans need to contribute to the CPS environment.

Multiple challenges related to implementing CPS are faced by the manufacturing industry. Some of these challenges highlighted by Lee et al. (2015) are transferring data to information hubs, hardware selection, making useful insights into the data, and system settings. Overall, the manufacturing industry is recognized to be one of the most advanced among other industries for CPS-enabled processes implementations and developments.

3.3 CPS in the Healthcare Industry

The healthcare industry environment and applications are very peculiar; therefore, healthcare CPS applications present unique challenges and opportunities. CPS in the healthcare industry is the vessel to provide improved services that alleviate people suffering and potentially saving lives.

One of the most significant differences in some of the applications of CPS in the healthcare industry is the types of sensing devices used. In a CPS-enabled healthcare perception schema, sensors are focused on patient's health; thus, sensors such as glucose-meter, heart rate, blood pressure, and others are prevalent (see Fig. 3.2). Information from these sensors is then transferred to databases for analysis and is used to automate processes that provide services to improve patient's health. In

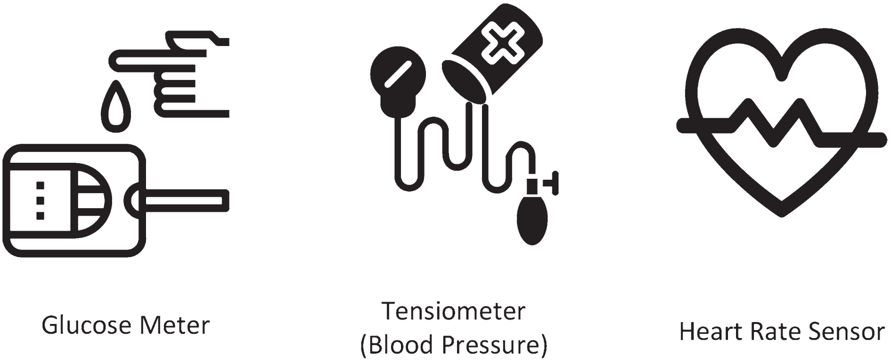

Fig. 3.2 Typical sensors in a CPS-enabled healthcare implementation

some cases, this information is shared among multiple healthcare facilities to enrich databases and create centralized healthcare systems (Liu 2015).

One application of the CPS in the healthcare industry includes CPS as the major collector and database for a healthcare facility. The types of data accumulated in these databases can include clinical data, human and materials resources management, and analysis of patients' behavior. The role and benefits of CPS are increased when useful information insights are created from all the data sources available. As noted by Haque et al. (2014), CPS provides advantages similar to other industries suchlike optimization or autonomy. However, specific applications of CPS for the healthcare industry are particular and more importantly, they bring additional reliance for the healthcare services provided such as monitoring and warning of healthcare staff.

The data in a healthcare system can be analyzed at different scales. A single patient health status can be the most basic scale for data, while a larger scale may consider the management of services in a whole healthcare facility or at a bigger scale can be the management of a network of healthcare facilities. A further application is to use this data to discover anomalies that raise alerts to a problem in the CPS healthcare systems at such different scales. E.g. Ahmed and Barkat Ullah (2018) proposed an anomaly methodology to make it easy to identify such anomalous patterns in healthcare facilities. Another use of CPS is the monitoring of multiple healthcare assets in a centralized fashion to improve the provision of services and improve healthcare for patients across an organization or healthcare system. As proposed by Sultanovs et al. (2016), a centralized healthcare architecture for improved management of multiple healthcare facilities based on CPS may improve health patients' services and potentially automate illness analysis and provide automatic treatment options. This is based on the premise that the monitoring of patient's health state and medical devices attached to them can serve as processing database to discover similar suffering sources, thus treatment to other patients in a network.

Heterogeneous data sources in CPS-enabled healthcare facilities and systems are still a problem, and accordingly, interoperability strategies still need to be developed to manage data adequately. Because of this, architectures and frameworks are being developed to tailor the big data obtained from these systems to gain valuable insights about the information offered (Yin et al. 2017). The human factor is a cornerstone for healthcare facilities; therefore, the human interactions with the healthcare systems and context-awareness abilities of CPS are of utmost importance to develop and implement. Besides, CPS enables quick information analysis, and immediate communication means to provide first responders the information they need to improve their response times for medical emergencies. Finally, CPS can improve the security and management of environmental conditions to provide the comfort of the patients and workers.

3.4 Smart Grid: CPS in the Energy Distribution Industry

The energy grid is a dedicated system to transfer energy from the generating sources to the users by means of energy transmission. Along with this transition, several intermediate processes happen in the grid to finally provide adequate and reliable energy needs to the users. However, along the transmission process, some factors or events can be in detriment to the quality of service provided or bring energy services to a halt because of internal or external issues in the grid system. The smart grid is known as a system with several cooperating and mutually interacted entities that work together to support the functionality of the power grid. For years, the infrastructure of the electric grid systems faced technical and reliability problems. The Smart Grid is a specialized CPS for better management and increased resilience of the electricity grid networks. It seeks to find solutions to challenges that arise from growing demands for service stability and incorporations of more energy sources, including renewable sources. It aims to optimize energy generation while providing more reliable services at all the grid levels (Sridhar et al. 2012). As such, the use of CPS helps develop a smarter and more efficient power grid system and has been valued as critical to a smart grid system. CPS provides a communication network that provides information to energy managers and helps to monitor the status of the network at any point to optimize the energy generation, and optimally keep the grid on check by implementing corrective and preventive measures. For that purpose, smart grid architectures seek to capture the intricacies between the electricity and information flow in the smart grid networks as shown in Fig. 3.3. As Khan et al. (2016) illustrate, electricity flows from utility providers to consumers, but at the same time, information is transmitted back to higher levels in the smart grid system (NAN to WAN) in order to optimize utility generation.

However, the smart grid requirements for real-time information and cybersecurity are more notorious and have a higher degree of relevance compared to other CPS applications. More than other industries, real-time monitoring, and information transmission is a requirement in the smart grid because electricity fluctuations can happen at any second and these fluctuations can damage user networks and devices, accordingly, elevating the risk on the reliability of the energy grid and many social

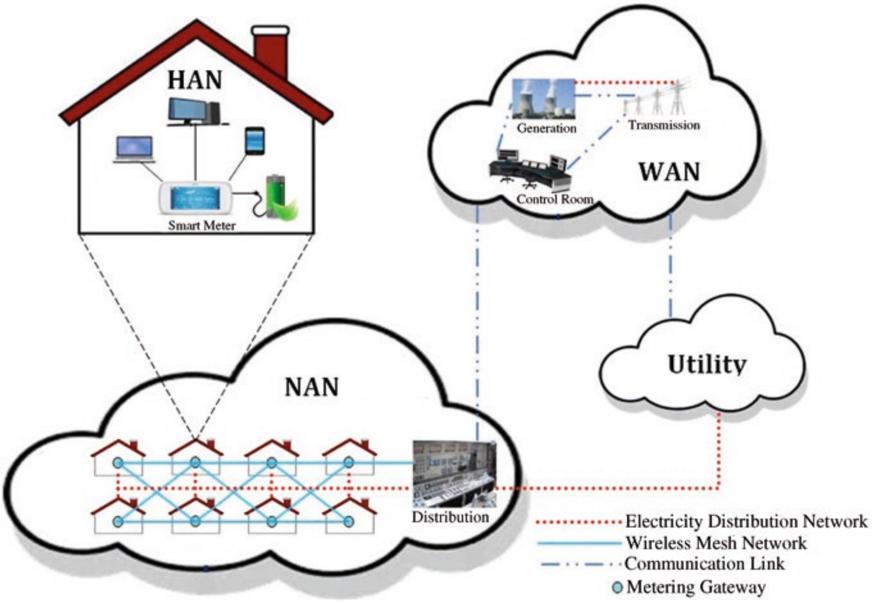

Fig. 3.3 Smart grid architecture and major network types: Home Area Network (HAN), Neighborhood Area Network (NAN), and Wide Area Network (WAN). Source: (Khan et al. 2016)

services. The real-time information sharing remains a challenge that continues to be in development (You et al. 2017). Cybersecurity on these networks is essential as the hacking of a network can cause service disruptions that also affect service reliability and potentially can be a privacy concern. Research has been conducted to address security issues at all levels of the smart grid which include standards for security to reduce vulnerabilities into energy meters, energy lines management, and security assessments to minimize risk in smart grids (Wang et al. 2011). An application of CPS in transactive energy management in smart grids is presented in Chap. 18.

3.5 CPS in the Transportation Industry

The transportation industry is encountering various problems, such as traffic jams and accidents. The use of CPS in the transportation industry seeks to sustain the daily operations for the movement of people, goods, vehicles, and the infrastructure needed to accomplish that. CPS also supports Intelligent Transportation Systems (ITS) by and supports real-time inspection of the transportation status for optimized performance of transportation and route planning systems. It becomes a vessel for the interaction between physical transportation elements and their virtualization to help to understand better and manage the ITS and traffic flow.

CPS in transportation includes numerous elements including the users, the vehicles, the infrastructure, the systems, and the systems of systems. Users include drivers of public transportation vehicles, passengers of public and private vehicles, vehicles, particular cars, buses, and rail and maintenance staff, operations staff, managers and others. The infrastructure can include the roadway infrastructure, the public rail transportation systems, or the city infrastructure. Systems can be the independent traffic operations, public, and rail operations that operate at a city level, and external systems such as buildings and other built facilities.

CPS in transportation can be described across different levels. Today's vehicles are becoming both a complex CPS element and CPS systems. Individually, vehicles can be considered CPS systems that incorporate sensors and intelligent decision making to sense their environment and provide feedback to the driver. An automobile can use CPS to sense its surroundings to enable the autonomous and safety systems that help relive drivers' efforts, assure roadway and pedestrian safety and potentially can improve the traffic flow. At a higher level, it can include communication among different vehicles employing vehicle to vehicle (V2V) communication that supports traffic flow and safety (Naufal et al. 2018). An even higher level of CPS implementation is the management of fleet operations for fleet services that help optimize goods transportation which not only benefits companies through lower fuel consumption but also helps reduce environmental impact and traffic congestion (Ma 2013). Relevant interactions such as vehicle to vehicle (V2V), vehicle to infrastructure (V2I), and vehicle to devices (V2D) were identified for preventive accident occurrence strategies. These interactions are also critical in academia, and research efforts are being undertaken to find the intricacies for reliable communications (Vinel et al. 2018).

Since transportation systems include mobile agents across multiple contexts, any CPS-based approach must first detect and recognize the context where actuation is happening. The context relates not only to the spatial constraints relative to agents' location but also to the behavior of the agents at a specific time and location. As Feng et al. (2017) explains, the actuation of CPS systems has to take into consideration the context of application in order to do relevant and accurate transportations affectations.

CPS in the context of public transportation systems has helped to better estimate bus/taxi arrival time by carefully monitoring and predicting the real-time operation of public transportation vehicles. As Cai (2014) reviewed, passengers, will have more accurate bus arrival times when CPS devices are incorporated into monitoring in addition to other information including the location data from sensors plus historical data that is shared among transportation networks.

A big problem in cities is traffic congestion which has been identified to be a significant factor in the citizens' productivity loss. Because of that, ways to reduce traffic congestion are of significant interests, and one of the approaches that researchers are exploring is to use CPS-based approaches to optimize traffic management at intersections by more efficiently managing stoplight signaling. Elchamaa et al. (2016) applied CPS to perceive vehicles' movement at intersections by using sensors and decision-making algorithms and autonomously optimize the waiting time for vehicles according to the traffic demand during certain events.

In contemporary urban transportation systems, mass transportation systems similar to the railroad and light rail are essential assets to move goods and people. CPS has been applied in managing these resources to optimize operations and increase the reliability of these services. Hatzivasilis et al. (2017) provide further insight into these applications by applying CPS in managing these assets. Specifically, CPS is used in these contexts to monitor exterior railroad route conditions. Safety management through CPS was also tested in cases when dangerous cargo was transported (Hatzivasilis et al. 2017). A through review of CPS based smart transportation and its applications is presented in Chap. 13.

3.6 CPS in the Aviation Industry

The applications of CPS in the aviation industry are viewed from many perspectives. CPS in the context of air transportation operations is being researched to accommodate the physical asset monitoring, from the boarding of the passengers all the way to the arrival at the gate along with the operations happening in all these processes, usually called gate-to-gate operations. The monitoring and potentially improved control of processes such as gate departure, takeoff, in-route, landing, taxing and gate arrival may produce efficiency gains such as improved safety, reduced emissions, better fuel consumption, and better air traffic control (Sampigethaya and Poovendran 2013). Figure 3.4 shows the shift in air transportation

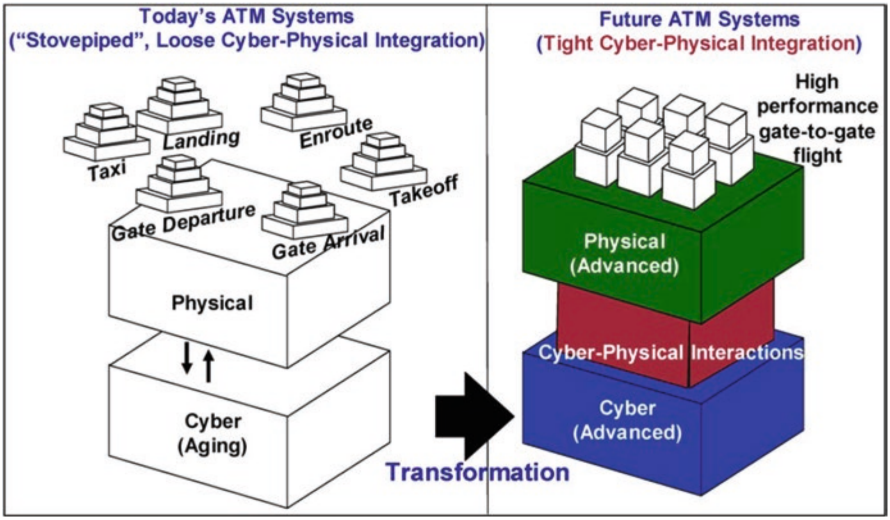

Fig. 3.4 Cyber-physical integration for the aviation industry. Source: (Sampigethaya and Poovendran 2013)

processes by including integrated CPS for gate-to-gate operations in contrast with independent systems used without CPS.

Besides, CPS applications inside the aircraft are also being studied and implemented. Some applications include the monitoring and autonomous control of aircraft systems to support the pilot's decision-making and information knowledge for safety operations during flight, take-off, and landing. Another application includes the monitoring of passengers and cabin systems to provide increased comfort and facilitate aircraft operations while in-flight and after flight operations. CPS is also supporting the maintenance operations for aircraft by reporting hazards when detected (Sampigethaya and Poovendran 2013). To simplify the Maintenance, Repair, and Overhaul (MRO) process to improve the availability of aircraft, Mertins et al. (2012) demonstrated the use of CPS as an effective solution.

Another application where CPS is being researched is green performance. This refers to the monitoring of the aircraft and flight routes to mitigate aircraft emissions. The approaches to achieve this include the monitoring of aircraft emissions to optimize fuel consumption and accordingly reduce emissions, and external factors such as temperature, wind speed, and others. It is expected that these data-rich systems help to facilitate adaptation to these new systems, but this is a gap pending to be bridged per the literature reviewed (Sampigethaya and Poovendran 2013).

3.7 CPS in the Agriculture and Farming Industry

The agriculture industry is facing challenges to sustain current and future production goals. Some of these factors are labor shortage difficulties, safety issues related to the agricultural work, and new technological innovations that need to be implemented, to name a few. CPS in the agriculture and farming industry is focused on efficiency. Based on this, the primary goals to implement CPS in the agriculture industry are to produce increased crop yields, optimize soil capacity to reduce pesticide usage and provide better environmental information so the plant condition can be better monitored. Within this context, the concept of precision agriculture and intelligent crop production are popular to accommodate the ideal agricultural practices for modernized agriculture practices.

Precision agriculture is a new paradigm for the agriculture industry to optimize agriculture practices based on implementing technology innovation in the field (Chen et al. 2015). Precision agriculture addresses the optimization problem by sensing the crop condition and the environment; therefore, a CPS approach is ideal for these cases. Because of this, frameworks to apply CPS in this industry have been studied and developed, e.g., a CPS framework for precision agriculture developed by Nie et al. (2014).

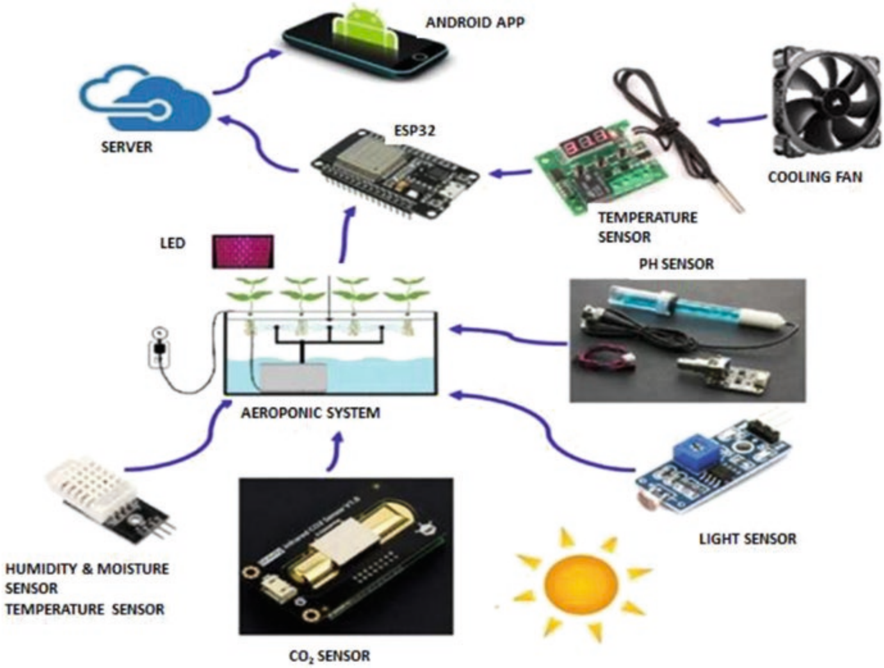

Fig. 3.5 CPS framework example for a remote monitored and controlled vertical agriculture system. Source: (Chuah et al. 2019)

One of the applications of CPS has explored means to support vertical farming. Chuah et al. (2019) evaluated a CPS approach for monitoring the plant environment and be able to control the parameters that affect the plant growth in this context. This framework makes use of CPS sensors to monitor plant and system parameters to automatically provide information to an internet-connected platform. Although the system is not autonomous, monitoring information is communicated to a user platform for decision-making, and actuators are then used to support the plant conditions and to support the plant growth.

Similarly, E and Zhu (2014), developed a CPS-based framework to monitor and control crop production by sensing the crop status and its environment to optimize yield production through real-time sensing and actuation (Fig. 3.5).

3.8 CPS in Education

CPS in education is being explored to enhance learning and training experiences at all levels. Enhanced education is being touted as a new frontier aided by technological advancements, including CPS. Reasons to promote such kinds of innovations include raising the interest of potential students in varied disciplines, e.g., Science, Technology, Engineering and Mathematics (STEM). The concept of Smart Learning Environments (SLE) in academic teaching agglomerates multiple concepts that affect the learning and teaching experiences in educational settings. The first set of factors concerns the learning environment itself and tend to offer a CPS-based SLE to enable autonomous hazard detections, human health status monitoring, facilities, and equipment status monitoring, and optimization of building resources. Additionally, the learning schema needs to adapt to SLE and mechanisms have to be established to enhance the learning experience and reduce distraction that the adapted systems can cause to the learning processes (Lei et al. 2013a). As such, the CPS-powered intelligent system can provide SLE with relevant and on-time solutions, prevent failures and hazards, and automatically improve the learning conditions for students or provide teaching tools to educators.

Different learning environments, including laboratories, have also been explored to examine how the implementation of CPS can enhance the learning experience. Smart laboratories have similar factors compared to SLE, but they should consider a more extended tracking of their users as their potential work has prolonged periods of time, e.g., in research laboratories, a research team can inhabit a lab space for months or years for prolonged daily routines. However, the utilization of resources, safety and hazard detection, human health status and resource usage monitoring are similar to SLEs in teaching environments. Also, the tracking of the activities in the lab environment can be of benefit to lab users or lab managers as reported by experiments under these settings by Lei et al. (2013b). Nevertheless, factors such as the inhabitant's health and occupancy status should be analyzed along a more extended period of time to detect chronical hazards that can be developed over continues exposure times (Lei et al. 2013b).

3.9 Conclusions

Despite differences in applications, the essential functions of CPS among different industries remain the same. Monitoring, data flow platforms, and data-rich environment applications are the most remarkable areas of interest in all the reviewed industries, both in academia and industry. Besides, CPS is perceived as the vessel for the applications of future technology advancements, particularly automation, visualization, and integration of systems. However, the current applications of CPS are still in development stages, and their maturity is expected to occur in the next few years. Among all the industries, the manufacturing industry is perceived to be the most advanced and the one where CPS has been found to have the most applications and relevance.

Some of the reasons why other industries are more reticent to CPS implementation include more challenging environments where CPS and technologies are harder to interact, more complex interactions among system elements, different human factors involved in the CPS implementation in these industries, and the industry itself to be more reticent to technology implementation. For example, the transportation industry is challenged by the environment where the CPS elements have to interact, while in the manufacturing industry, the environment can be more controlled and predictable. The agricultural industry is challenged by the interaction among the crops and alien living creatures (pollinators, bugs, others) as CPS system elements that unexpectedly can affect the system in unexpected ways.

The construction industry is currently following the steps of other industries by discovering the benefits and challenges that they experienced. Learning from the experiences in other industries may help the construction industry to ease the implementation of CPS and investigate the lessons learned and solutions that have not been explored before.

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Chapter 4

Cyber-Physical Systems-Based Component Tracking and Operation

Abiola Akanmu, Chimay J. Anumba, and Johnson Olayiwola

4.1 Introduction

The construction of building and civil infrastructure systems involves assembling diverse building materials/components to meet a set of prescribed design requirements. These design requirements have traditionally been represented as two-dimensional drawings and in recent years, as virtual 3D design models. These virtual design models are either be in the form of computer-aided designs (CAD) or information-based models, known as Building information models (BIM). These virtual design models contain digital object representations of physical building components whose graphical simulations illustrate the physical layout, operational and functional as-planned design requirements. For example, a door object could contain attributes of the door, including the types and quantities of materials, installation dates and possible changes to the installation of the door. As the building moves through the lifecycle from planning to design to construction and to facility management, information needed by the stakeholders to effectively interact with the door can be embedded in the door object. This information, if effectively linked with the corresponding physical building components, could inform the timely, accurate and safe delivery of the construction projects, as well as the management of the constructed facility.

Advances in information and communication technologies present an excellent opportunity to link the physical components with their corresponding representations in the virtual model. Such linkage between these two facets of components

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could facilitate bi-directional coordination such that changes in one environment are automatically reflected in the other (Anumba et al. 2010). This process of maintaining consistency between virtual and physical components is termed component-based cyber-physical systems (CPS). Cyber-physical system has emerged as a promising approach to improve existing efforts of component tracking, installation, and maintenance. CPS involves tightly knitting physical components and systems with cyber (e.g., virtual models, sensors, algorithms, and actuators) resources to form an integrated system that intelligently responds to changes in the real world (Poovendran 2010, Rajkumar et al. 2010). CPS considers the close interactions between the physical system and its cyber system both in time and space dimension. These interactions are usually governed by events, which occur in physical space and should autonomously be reflected in its cyber space. This is particularly important for construction projects which are typically characterized as dynamic and prone to uncertainties or unforeseen circumstances. If construction projects are to be delivered as-planned, there needs to be mechanisms for tracking the status of the components and assemblies, and for controlling the construction process. In the construction industry, control could be human-centered, automated or a combination of both. This chapter describes a structure and framework for the implementation of component-based cyber-physical systems in the construction industry. The framework includes drivers and requirements for cyber-physical systems, system architecture, some early developed and implemented applications and highlights challenges and barriers to achieving and implementing future component-based CPS are presented.

4.1.1 Drivers for Component-Based Cyber-Physical Systems

Construction project management activities have been identified as a closed-loop system, involving continuous forward flow of building/design information and feedback flow of project or facility state information [24]. Hence, to maintain this closed system, there needs to be an integration of the design model and the physical construction/constructed facility. This integration is considered vital from the perspectives of change management, progress monitoring and control, as-built information, and operations and maintenance. These aspects are discussed below.

4.1.2 Progress Monitoring and Control

An important aspect of construction project management is the ability to effectively monitor and control construction work. Real-time monitoring of construction projects is necessary for ensuring that completed projects comply with project specifications, budget, and schedule. Project conditions such as resource constraints, technical complexity, significance of timely completion, and substantial costs put great emphasis on the planning, scheduling, and control of construction operations. When construction projects commence, they are not self-regulating. They require real-time monitoring if events are to conform to set standards or plans. Tying the physical components and assemblies with their representation in the as-planned model, will enable the project team to understand the context of the project and thus be able to make real-time interventions.

4.1.3 Change Management

The construction industry is very complex, as project development generally comprises several phases and each phase requires a diverse array of specialized services and the involvement of numerous participants. How information is managed amongst these project participants is important as this could affect the project outcomes. The ability of project teams to understand what is going on at every stage of a project is critical to the successful completion of construction projects. Every team member needs timely and accurate information about the progress of the project, and status in comparison to the initial plans so that they can react quickly to project issues. Also, when design changes occur, they need to be shared accurately, consistently and in a timely manner between the project team members so as to reduce risks such as time and cost overruns. Similarly, when changes are made on the construction site, there is a need to document these changes such that they can be utilized in the operations and maintenance phases. Virtual models have the ability to represent as-built and as-planned progress discrepancies. Thus, maintaining consistency between virtual models and the physical construction will enable on-site personnel to effectively visualize changes. Furthermore, this integration will enable on-site engineers to acquire and send real-time data from the construction site to the project managers in the office for effective decision making.

4.1.4 As-Built Information

As-built drawings/models represent the contractors' certified record of what was built and it is extremely important to owners for the purpose of maintenance, major renovations, and demolition, especially for critical but typically hidden services infrastructure. Sometimes, the worth of the final delivered as-built drawings is commonly limited significantly by leaving their creation, as an afterthought, to the end of the project. This often results in large un-correlated collections of inaccurate, incomplete information with limited utility for describing exactly what was built. This also results in the loss of opportunity to use continuously updated as-built models to manage on-going work and identify deficiencies early enough to avoid rework. Effectively integrating virtual models and the physical construction will enable recordings of existing conditions of structures for the purpose of renovations, re-modeling, and historical restoration projects.

4.1.5 Operation and Maintenance

Several authors have identified that limitations in data transfer between maintenance workers and a central facility management (FM) system result in lower data quality, longer service process times, and ineffective capturing of component maintenance history. Linking the virtual components with the physical components in a constructed facility will enable storing and retrieval of relevant information required for maintenance. This integrated approach can also provide remote access to the constructed facility for the purpose of identifying and controlling the physical components in the building systems such as HVAC, lighting and electrical systems. This is particularly beneficial as it enhances sustainable practices in buildings.

4.2 Requirements of Component-Based CPS in Construction

4.2.1 Real-Time Capability

Building components undergo a series of processes from the planning phase of construction projects to the operations and maintenance phase of the constructed facility. Real-time capability of component-based CPS means that instructions or information required to engage with the components needs to be transmitted timely. Real-time information or data about the context, handling, and condition of the components is critical for quickly identifying and resolving issues or risks. During the construction phase, supply chain, installation, and resource status are critical for decision making and control of construction projects. Being able to effectively capture and relay this information to the project stakeholders is significant. Researchers have identified the benefits of real-time monitoring for supply chain management (Irizarry et al. 2013), site layout management (Akanmu et al. 2016a, b), progress monitoring (Azimi et al. 2011, Ranaweera et al. 2012), inventory management (Kasim et al. 2012) and safety management (Giretti et al. 2008, Cheng and Teizer 2013). Likewise, access to real-time conditions of installed components such as heating ventilation and air-conditioning systems can enhance early diagnosis of potential equipment failure, thereby improving the efficiency and comfort of building occupants (Liang and Du 2007, Djuric and Novakovic 2009).

4.2.2 Adaptability

Component-based cyber-physical systems need to be able to sense and respond to changes, uncertainties and abnormalities that typically occur during the lifecycle of buildings and civil infrastructure systems. In construction, variations in site conditions and unforeseen circumstances such as different weather conditions, equipment failure and human factors relating to delays and performance, trigger changes. Construction projects need to be monitored in order to quickly detect and respond to these deviations – this is significant for ensuring that the project stays within budget and meets the schedule. Furthermore, whether the anomaly is naturally, accidentally, or maliciously induced, in terms of a sensor default, failure of any of the part of the system, or the infrastructure malfunction, the component-based CPSs must be able to adapt to whatever situations they encounter (Xia et al. 2013, Wan et al. 2015). The component-based CPSs must virtually reorganize, reconfigure and heal to yield the best possible system performance. Such systems should also be scalable and tolerant to risks triggered by these uncertainties. In addition, to cope with uncertain and emerging situations, component-based CPSs should be self-aware and context-aware. For example, be able to anticipate needed information and deliver these based on the context of the beneficiary.

4.2.3 Networked

Buildings and civil infrastructure systems comprise of a network of co-dependent components and systems. These components depend on each other in terms of information, schedule, resources, and personnel. The components also share allocations of workspaces (Chavada et al. 2012), equipment and temporary structures. During the operations and maintenance phase, the components collaboratively function to provide shelter and comfort to the occupants. For instance, the elements of the building envelope, heating, cooling, lighting, and electrical systems function like a system of systems to improve indoor air quality and thermal comfort of building occupants. Understanding the dependencies between building components is critical for building an effective network of communication. In component-based CPS, building components will need to be mediated by networks and software that can facilitate interactive and cooperative behavior.

4.2.4 Predictability

Predictability refers to the ability and degree to which the behavior and state of construction components and processes can be predicted qualitatively or quantitatively (Lee 2006, Sangiovanni-Vincentelli et al. 2012). The dynamic nature and uncertainties inherent in construction projects make it difficult to predict project outcomes – this makes construction projects a candidate for CPS. Predictable construction activities will need to assure the outcomes of the system's behavior whenever operational while also meeting all system requirements. In component-based CPS, sensing systems, as well as control technologies, should be well adapted to the construction processes, anticipate changes in the physical process, risks posed to projects and amend their features based on the context of the construction environment. Some current construction automation solutions allow for real-time monitoring and control but are insensitive to project uncertainties (e.g. changing environment, project scope and delays) and time-predictability.

4.2.5 Human-in-the-Loop

The construction industry is a labor-intensive sector. Applicable component-based CPSs must consider human participants as a significant component. Component-based CPS must be instinctive and integrate with worker's behaviors in construction environments (Munir et al. 2013). This is important for communicating needed information and assisting the decision processes of construction workers. Although there is significant data and experience on the performance of existing automated systems deployed in the construction industry, the extent to which human behavior has been modeled and integrated into the design of systems has varied. A-lot of the anticipated goals of component-based CPS, in terms of zero fatalities and injuries, can be achieved through the design of systems that have a complete understanding of human behavior under diverse conditions such as emergency situations (Munir et al. 2013).

4.2.6 Reliability

Reliability refers to the degree of accuracy to which component-based cyber-physical systems perform their function (Mitchell and Chen 2013). Certifying the capabilities of component-based CPS as being able to accurately perform their functions does not mean that they actually can. Component-based CPSs are expected to operate reliably in dynamic and uncertain environments. For construction safety applications involving equipment or postures, a slight change or deviation from planned performance may result in fatalities (Yuan et al. 2016). Uncertainties in knowledge, characteristics, potential errors and outcomes in construction processes should be quantified during the design of component-based CPSs.

4.3 Component-Based Cyber-Physical Systems

Key Features Component-based CPS bridge physical components with their virtual representation through sensors/data acquisition technologies and actuators to form closed loops (Dillon et al. 2011, Chen et al. 2015). Several authors have identified such closed loops systems as critical for facilitating effective tracking and control of construction projects (Navon and Sacks 2007, Turkan et al. 2012). Component-based CPS consist of two key elements: a 'physical to cyber' bridge

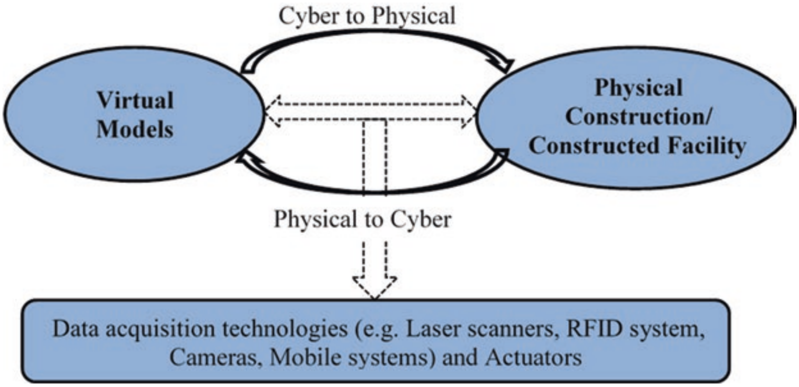


Fig. 4.1 Key features of component-based CPS

and a 'cyber to physical' bridge (Xia et al. 2011, Bordel et al. 2017). These are described as follows (see Fig. 4.1):

- Physical to Cyber Bridge: This involves sensing the elements of construction processes and activities using sensors and data acquisition technologies. Information about the condition and dynamics of the construction process are captured and related to other cyber elements for processing.
- The Cyber to Physical Bridge: This represents the actuation which indicates how the sensed information affects the system. Actuation is taken to mean conveying the right information to enable quick decision making with the sensed information and/or using the sensed information to physically control construction activities, resources, and components.

4.3.1 Component-Based CPS via Bi-directional Coordination

The need to maintain consistency between the as-planned design and as-built models has resulted in the development of a bi-directional coordination approach to Component-based CPS (Anumba et al. 2010). The bi-directional coordination approach involves integrating virtual models and the physical construction/constructed facility for consistency maintenance. Unlike traditional integration approaches which only passively monitors the physical world, this approach enables tight interaction and coordination between the virtual and physical world. Early attempts at implementing component-based CPS via bi-directional approach include construction component tracking and placement (Akanmu et al. 2013a, b), site layout management (Akanmu et al. 2016a, b), and postural monitoring and control. These are represented in Fig. 4.2.

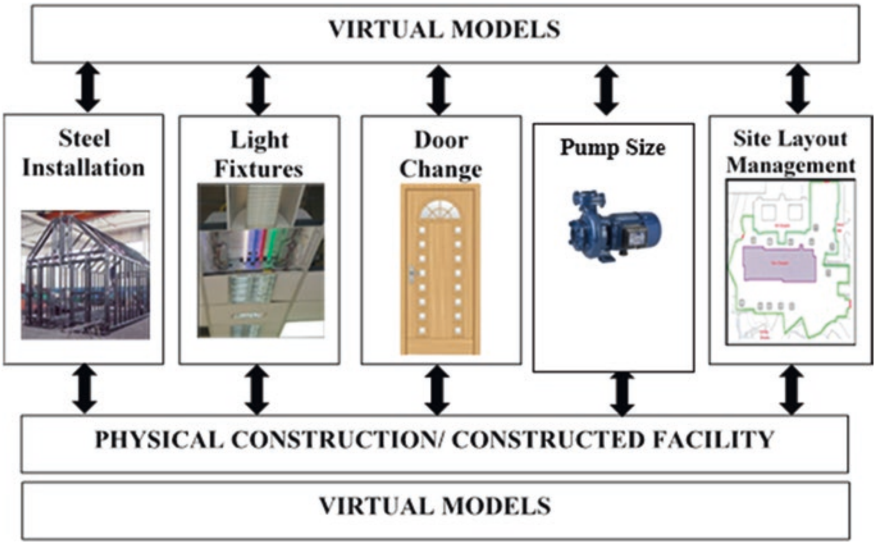


Fig. 4.2 Bi-directional coordination approach to component-based CPS

4.3.2 System Architecture for Bi-Directional Coordination Approach

The bi-directional coordination approach is illustrated in the system architecture shown in Fig. 4.3. The system architecture brings together the functionality and the key enabling technologies necessary for implementing bi-directional coordination between the virtual models and physical representations. The architecture is based on five layers, which are explained in the following sub-sections.

4.3.2.1 Sensing Layer

The sensing layer consists of sensors and other data acquisition technologies. The sensors monitor different aspects of the construction process/constructed facility, e.g. radio frequency identification sensing systems for tracking the status of construction resources. Depending on the type of sensor used, this layer can also provide the construction personnel access to control decisions (e.g., information captured in the radio frequency identification (RFID) tag memory or information that can be accessed through the RFID tag ID). Other data acquisition technologies such as smartphones can also be used by construction personnel on-site to physically extract project status information. This layer serves two purposes: it provides access to sensed data from the sensing layer and enables the entry of information through the user interface.

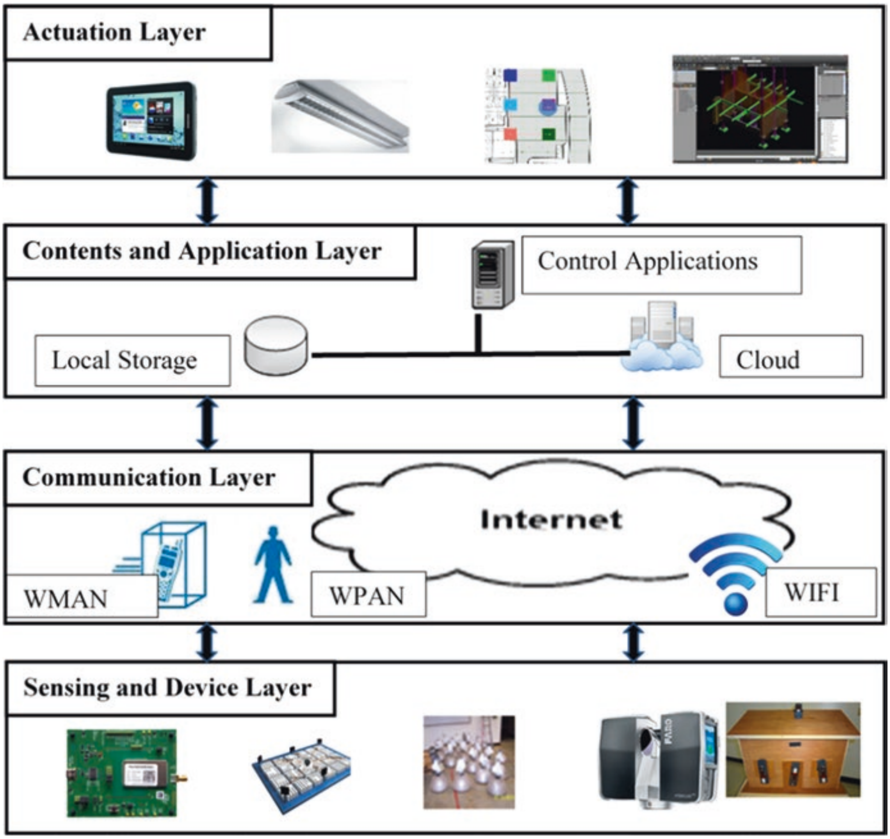


Fig. 4.3 System architecture for Bi-directional coordination approach to component-based CPS (Akanmu et al. 2013a, b, Kan et al. 2019)

4.3.2.2 Communication Layer

The communication layer serves as the data processing and communication unit. This layer converts the data obtained from the sensing layer into formats readable by the contents and application layer. The communication layer contains the internet and wireless communication networks e.g. wide area networks and local area networks. These communication networks also connect the sensor and data acquisition technologies to allow for networking and information sharing between workers at the job site and the field office.

4.3.2.3 Contents and Application Layer

The contents and application layer contain the local database, database server, and control applications. The type of control application depends on the context application to which the system is put. For example, control applications could be machine learning algorithms. This layer stores, analyses and is constantly updated with information collected from both the communication and actuation layers. The stored information includes project management data (such as resource type and status). The control applications use the sensed data from the database to make control decisions which can be either visualized using the virtual prototype in the actuation layer or used to control the physical system such as equipment and postures.

4.3.2.4 Actuation Layer

Depending on the type of control needed, the actuation layer could provide access to critical information needed for decision making or physically control the physical environment using actuators. The actuation layer contains the virtual prototype which is accessed through the user interface or a mixed reality environment. The virtual prototype enables the user to visualize how the sensed information (from the contents and storage layer) affects the system. The user interface enables the user to visualize and monitor the sensed information from the contents and storage layer. The user can also embed control decisions into the virtual prototype through the user-interface to be accessed in the device layer.

4.4 Case-Studies

4.4.1 RTLS-Based Integration of Virtual and Physical Components

This application describes how bi-directional coordination between the virtual model and physical construction was applied to track the installation status and the documentation of each component of a laboratory-scale prototype of a building (Akanmu et al. 2012). A virtual model of the prototype was created using Autodesk Navisworks. The purpose of the virtual model is to enable visualization of the real-time status of the components. The laboratory-scale prototype consists of nine detachable components (Fig. 4.4). Each of the components was tagged with the tags of the RTLS system. The RTLS system obtained from Identec Solutions consists of real-time RTLS tags, RTLS readers, satellite nodes and an ‘i-Share’ position server. As each tagged component is displaced, each i-SAT node determines its proximity to each of the tagged components. Each i-SAT node sends the coordinate information to the tags. The individual coordinate data are read from the tags by the RTLS reader and transferred to the i-Share software. The i-Share software computes the relative distance of each tag and sends this to a Web interface. The database is constantly updated with data from the Web interface. To bind the tagged components with their virtual representations in the model, two applications were developed using Visual Studio.Net: CPSPlugin and Client Application. The client application

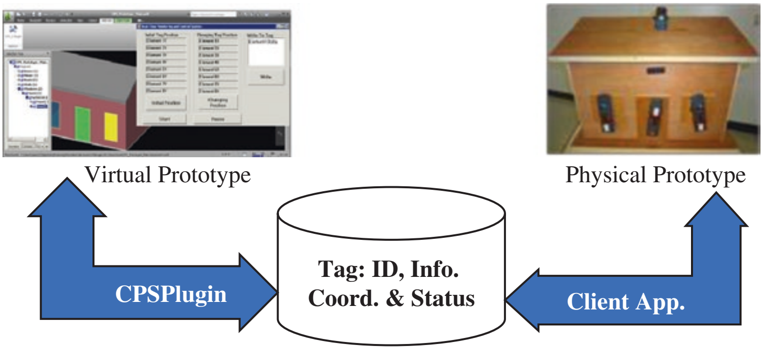
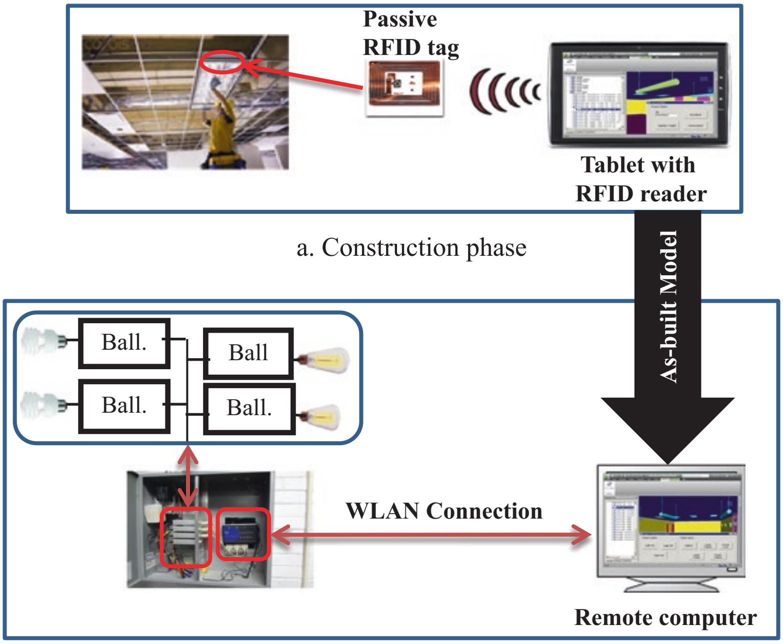


Fig. 4.4 Overview of RTLS-based CPS integration

links the RTLS tags with the database by tracking any updates to the tags and virtual model and writing these to the database, and any update from the model writing. On the other hand, CPSPlugin facilitates interaction between the virtual model and the database. If any of the tagged components are moved, CPSPlugin monitors or listens for any change in the coordinates (or status) of the tagged component in the database and reflects this change in the corresponding virtual component in the model. The affected component is highlighted (e.g. by a color change). This color change in the virtual model enables the model coordinator /project manager to remotely monitor the progress of tagged components. If a change or update is written into a virtual component in the model, the client application captures and writes the change to the RTLS tag on the corresponding physical component. Conversely, if the information in the RTLS tag is updated, the client application captures this information and writes it into the property of the virtual component. The affected virtual component is highlighted to notify the model coordinator of the update.

4.4.2 Light Fixture Tracking and Control

The locations of individual items of bulk materials (such as light fixtures) within a building are not easily differentiable; as such, facility managers cannot control each item. This application implemented by Akanmu et al. (2013a, b) (shown in Fig. 4.5) focuses on identifying and tracking the installed locations of light fixtures for the purpose of improving energy management in buildings. A virtual lighting model was designed to be used in tracking the status (e.g. installed, uninstalled, light’s on, light’s off, ballast failure and power failure) and controlling digitally addressable lighting systems such as the DALI laboratory on the Pennsylvania State University campus. The light fixtures in the laboratory are currently controlled using DALI system by Tridonic Systems. The DALI system consists of a device server, bus master, and light fixtures. The device server collects and transmits control messages from the fixture ballasts. The control messages are used to control the fixture



a. Construction phase

b. Operations and maintenance phase

Fig. 4.5 Overview of light fixture tracking and control (Akanmu et al. 2013a, b)

ballasts via the bus master. A middleware was developed to link the virtual components in the lighting model with the physical RFID tagged fixtures on the DALI system. The middleware (1) collects the tag ID from RFID tags on light fixtures; (2) enables binding of each tag ID with the corresponding virtual light fixtures; (3) monitors the bus master for messages or signals from the fixtures to update the virtual model; and (4) enables each virtual fixture to be controlled from the interface of the virtual lighting model.

Since the system was designed to be used by both lighting contractor and facility manager/owner, the system has two facets: Track and Bind, and Progress Monitor and Control. With the Track and Bind, lighting contractors can scan a tagged fixture. When the tagged fixture has been scanned, the tagged ID is captured, and the number appears in the virtual model. The contractors can now decide to track the status of the scanned fixture (installed or uninstalled) or modifying the property in the virtual model. With the Progress Monitoring and Control, facility managers can send messages in the form of IP addresses through the device server to the bus master. The bus master understands this message and controls the light fixtures. The bus master also monitors the light fixtures for messages on the status of the fixtures.

4.4.3 Site Layout Management

This application describes how bidirectional coordination between virtual site models and the physical construction site environment can enhance effective monitoring and utilization of site spaces (Akanmu et al. 2016a, b). This addresses the issue of time wasted and safety risks associated with searching for available spaces to store materials. The application whose workflow is shown in Fig. 4.6, illustrates a laboratory-scale implementation of an automated site layout generation system on the Western View Apartment project in Kalamazoo, Michigan. A BIM model

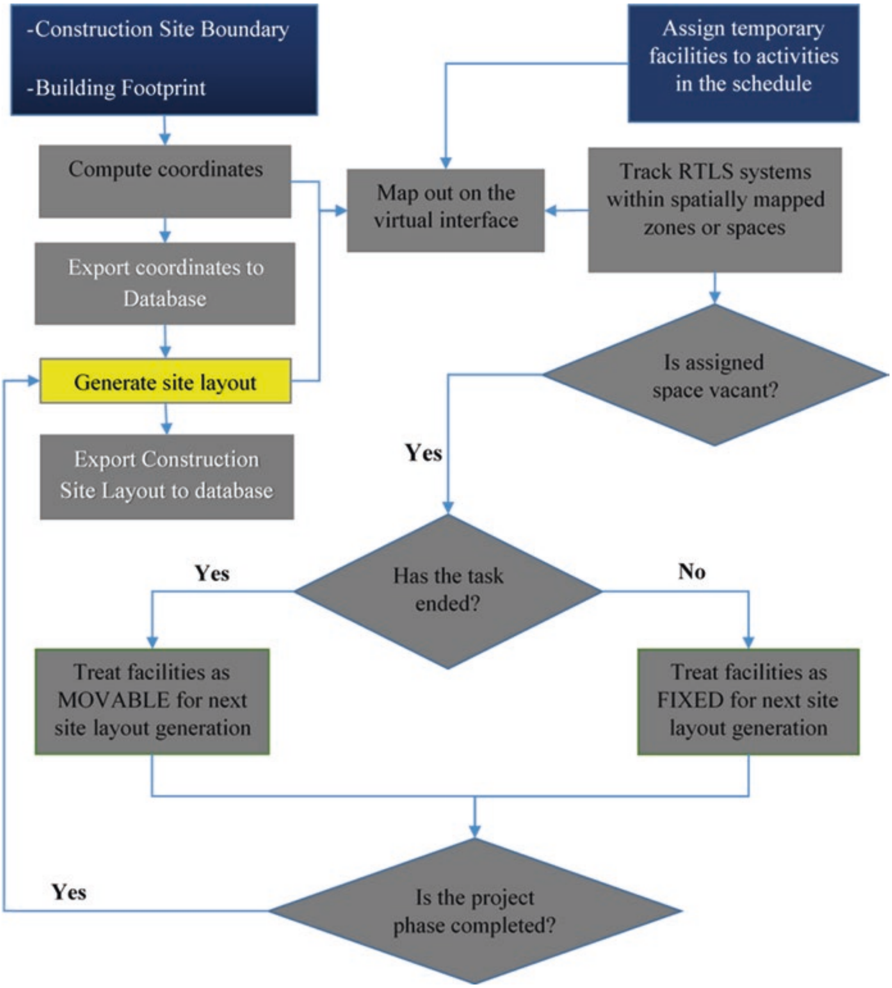


Fig. 4.6 Site layout management workflow (Akanmu et al. 2016a, b)

and schedule of the project were obtained from the project manager. Workers and materials were tagged with the RTLS tags. The RTLS system determines the real-time location of tagged materials/components within spatially mapped zones such as the construction site. A middleware that coordinates between the virtual site model and the physical construction site for generating and managing site layouts was developed. The middleware integrates (i) the project information from BIM, (ii) the status of construction resources obtained from radio frequency identification real-time location sensing (RFID-RTLS) system and (iii) genetic algorithm for optimizing the placement of site resources. The coordinates of the boundary of the construction site and the as-planned facility were obtained from the project manager and represented in the virtual site model. This is important to determine available spaces for staging materials and equipment. The middleware collects the site information from the virtual site model, divides the available site area into grids and stores the coordinates of the grids in the database. Within the BIM model, the middleware provides a platform for the project manager to insert the type of temporary facilities or site spaces required for executing each activity in the schedule. For the first phase of the project, the project manager assigns temporary facilities for each activity to be executed in the first phase. The middleware collects and stores this information into the database. Where an activity requires more than one temporary facility or site space, during the first phase of the project, the project manager inserts an estimated frequency of trips between the temporary facilities. The frequency of trips represents the rate at which a tagged worker interacts with or transitions between associated temporary facilities to complete work. The database sniffer from the middleware triggers the optimization algorithm to generate the site layout. The genetic algorithm uses the information contained in the database such as the coordinates of possible locations, type of activities in the first phase of the project, the temporary facilities or spaces needed for the activities and the frequency of trips between the facilities, to generate the optimum site layout. The middleware stores the first site layout in the database and also displays it on the virtual site model.

For the subsequent project phases, the middleware tracks the actual frequency of trips made by tagged workers between the temporary facilities or assigned spaces, the availability of the spaces (by tracking if there are any tagged materials within the spaces), the type of activities and required spaces, to generate the site layouts. If there are no tagged materials within the spaces, this means that the space is vacant and the middleware checks the schedule within BIM to determine if the task/activity associated with the temporary facilities is completed. If the task is completed within the current phase, the facilities are registered as “movable” and can be considered as free spaces in the next site layout generation. If not, the facilities are registered as “fixed”.

4.5 Challenges

4.5.1 Life-Span

Lifespan determines how long a data acquisition technology will be used before replacement or battery replacement. Some data acquisition technologies can be left on the facility for long term monitoring purposes while others can only be left for short term data capture and monitoring purposes. For example, real-time location sensors have a battery life ranging from 3–5 years depending on the frequency of use. This has major implications for the deployment of this and similar technologies.

4.5.2 Cost

Cost is an important factor in the selection of data acquisition technologies for tracking construction components. When selecting data acquisition technologies, the contractor needs to know the value-added benefit of deploying sensors and/or other data acquisition technologies. For example, a contractor may want to consider using a barcode instead of a passive RFID tag because of the cost difference. This is appropriate if he only needs to undertake simple tracking of components. However, when high-level tracking and/or bi-directional coordination is required, the cost becomes a lesser factor compared with the desired functionality.

4.5.3 Trust Issues

Trust is a persistent theme typically identified as a potential barrier to the uptake of component-based cyber-physical systems. Contractors usually have concerns about the unauthorized attempts to move component sensors from one component to another. Sub-contractors could interchange these tags for deceptive reasons such as trying to show that certain components have been installed when they have not.

4.5.4 Fragmented Nature of the Construction Industry

Due to the fragmented nature of the construction industry, there have been concerns about who bears the cost of component-based CPSs. Specifically, the concerns have related to strategies for sharing costs and how to determine stakeholders with the maximum benefit from such a system.

4.6 Conclusions

There are several potential benefits of component-based cyber-physical systems in the architectural, engineering and construction industry. These benefits include access to real-time progress information which will aid the construction project team in quick decision making and the potential for enhancing real-time communication and collaboration between the personnel on the job site and the office. Another benefit is that the proposed approach can facilitate improvements in facility management practices by enhancing the current process of as-built documentation, which will aid performance monitoring and control of the constructed facility. By demonstrating the potential of component-based cyber-physical systems, this chapter opens door to more cyber-physical systems applications in the construction industry. In spite of this potentials, opportunities exist in the area of how to design construction projects that provide information needed by the project team, yet requires minimal development and maintenance cost, software, and is reliable. Responding to these challenges requires significant advances in the state-of-the-art. Tremendous multidisciplinary approach is required to understand and develop methods, science, models, architectures, and solutions for more sophisticated component-based cyber-physical systems.

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Chapter 5
Construction Progress Monitoring Using Cyber-Physical Systems

Jacob J. Lin and Mani Golparvar-Fard

5.1 Introduction

Leveraging the unprecedented growth of data collected through mobile devices, drones, laser scanners, rovers and sensors on construction sites today (Ham et al. 2016; Han and Golparvar-Fard 2017), CPS technologies enable continuous progress updates from the downstream to establish the bidirectional communication cycle for effective project controls. With the recent development of computer vision and robotics in construction and the adaption of n-dimensional Building Information Modeling (BIM), the collected data are processed and integrated with BIM, project schedules, and used to compare between Reality and Plan for completing the feedback loop of CPS in construction progress monitoring (Lin and Golparvar-Fard 2018). This CPS for construction progress monitoring could improve the process of project control and enhance communication, coordination, and planning during the project execution. A typical process of project control usually includes (1) weekly plan coordination; (2) progress and issue tracking through job walks; (3) progress and issue documentation; and (4) plan review and adjustment. To accomplish the aforementioned process, the CPS needs to have a complete workflow from data collection, progress monitoring, activity analysis to reporting and decision making. Research has been investigating automated data collection through drones, rovers, and sensors; progress monitoring and activity analysis through the latest computer vision techniques such as material classification, object detection and tracking; reporting through color-coded models with predictive data analytics and digital daily construction reports. CPS that integrates the components above with project control theories and construction management workflow is a potential solution that

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addresses the drawbacks of the current status of project control through progress monitoring.

Efficient progress monitoring provides project stakeholders- owners, contractors, subcontractors- the updated information for project control decision making (Golparvar-Fard et al. 2011; Yang et al. 2015). With the construction put in place value surpassing $1.2 trillion (U.S. Census Bureau 2019), reports still show workers spend about 30% time of the week on solving avoidable issues such as looking for information and 50% of rework are caused by miscommunications. To improve the efficiency of construction, research has been focusing on the development of project control theories and progress monitoring technologies.

Project controls theories such as Last Planner System (Ballard 2000) has achieved better planning and communication that stabilize workflow by preventing direct work from upstream variation and uncertainty. Even though the benefits and achievements are widely documented, it remains more of an art than science to accomplish its full potential throughout the construction lifecycle and across different projects. Recent empirical studies indicate that the implementation of the control mechanism requires full commitment from all project team members and a dedicated champion in a relatively long learning process. With the absence of the champion, the project control workflow could easily revert to traditional practices (Leigard and Pesonen 2010; Sacks et al. 2010, 2013; Gurevich and Sacks 2014; Dave et al. 2015). While these challenges are mostly attributed to the organizational and people process involved in implementation, there is a growing interest to leverage production control theories with progress monitoring technologies such as CPS to better understand, analyze and communicate the performance problems while preserving a two-way communication information flow.

Research has developed CPS that leverages the visual data collected on the construction site and applied state-of-the-art computer vision techniques to produce 3D reality models of ongoing operations and automatically organize and manage them over project timelines. The integration of these models with Building Information Modeling (BIM) and project schedules enables deviation analysis between Reality and Planned to better communicate the production status through color-coded models and reports generated by predictive data analytics (Lin et al. 2015; Lin and Golparvar-Fard 2016, 2018; Han and Golparvar-Fard 2017). However, to successfully implement this CPS system for progress monitoring requires four key components:

Data Collection Desired frequency and completeness is necessary to sustain a smooth information input for progress and activity monitoring. The current practice of data collection still highly relies on manual procedures where quality and quantity usually do not meet the requirements for efficient project control. Progress monitoring data collected on construction sites can be categorized into visuals, sensors and text data with a range of formats from photos, videos, texts to laser scans. The collection process can be through commodity smartphones, drones, rovers, and different vehicles. To ensure the quality of the data collection process can produce informative data for progress monitoring, recent research mainly focused on areas such as completeness of reality models, feasibly integrated platforms for different environments, efficient data collection strategy driven by change detection.

Progress Monitoring Providing timely progress updates of the Reality and comparing it against the Plan model can keep a smooth information flow of production. Previous research presents a typical 3D reconstruction pipeline to create 3D geometric Reality models from hand-held cameras and registered to the 4D (3D + time) Plan model. Geometry-based and appearance-based progress monitoring techniques are performed to automatically analyze the space occupancy and material from 3D models and images for progress status. However, there are still plenty of open research problems and challenges to fully automate the process. For example, improving the efficiency and reliability of image-based reconstruction, material recognition, geometry analyzation, and camera viewpoints optimization.

Activity Monitoring Near real-time analysis of worker activities and equipment are used to help the management of onsite construction. Current practice is expensive, labor-intensive and incomprehensive due to the inefficiency of the manual procedure, inability of covering multiple locations and restrictions of computational power. Research has focused on developing camera networks that could track and connect different locations, and leveraging the recent development of machine learning and deep learning to improve the efficiency and accuracy of worker and equipment detection.

Reporting Visualizing the analysis result in an intuitive interface and an accessible platform is important in construction to complete the feedback loop of CPS. The interface needs to convey the analysis in construction grammar and express all critical states and changes associated with the Reality model. Research has used traffic light metaphor on BIM models to present the status of progress through web-based platforms. The analysis was also presented in the form of charts and figures in dashboards or in typical spreadsheets. These reports are used in the current construction workflow to improve and enhance the decision-making process, such as (1) 3-week look-ahead scheduling and coordination among key stakeholders of a project (state-of-the-art practice), and (2) daily operation planning by job site superintendents and foreman to set performance targets for their workforce and study potential improvements (Fig. 5.1).

With the current research advances in each domain significantly but separately, this chapter provides a holistic view of how to integrate the bits and pieces to complete the CPS for construction progress monitoring. In the following section, an overview of the state of the current construction industry is presented from a project control perspective with specific practical problems. Next, the opportunity of CPS using visual data as a source for capture, analytics, and representation of Reality and Planned data on construction projects are discussed. Next, we present the data collection process and the latest research on improving and automating this process through robotics and computer vision. We also discuss how the cutting-edge

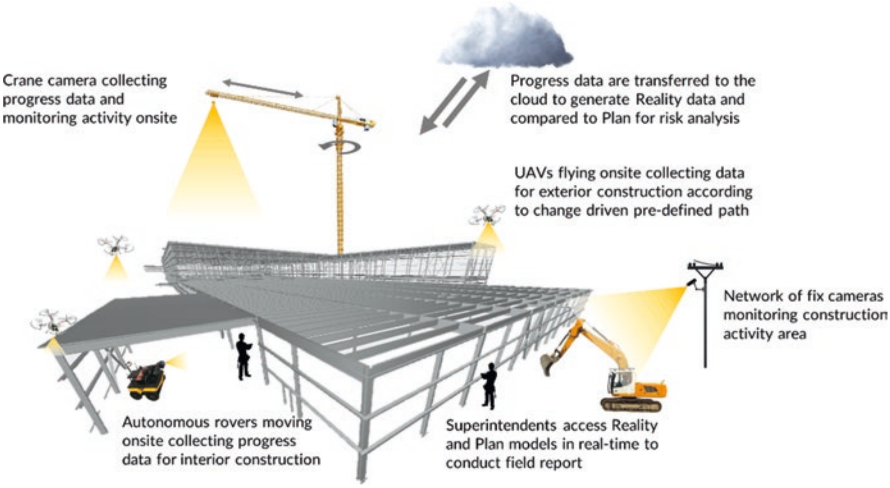

Fig. 5.1 The CPS contains data collection, progress and activity monitoring and reporting. The UAVs, rovers and network of fixed cameras are performing change-driven autonomous data collection, the cloud system processes the collected data and analyze the production rate and progress and provide an action plan for the project managers' decision-making process

computer vision and machine learning techniques such as deep learning, object detection, and Structure from Motion together with BIM and schedule are integrated and applied in the context of CPS to enable performance monitoring at both project task and operations level. The comparison of reality vs. plan will be discussed in detail for progress monitoring. For each use case, we will provide a concise literature review and assessment of current state-of-the-art solutions in the market, and will discuss the key underlying methods and recent solutions in detail. We will demonstrate their performance in the real-world by using a building project case study. The challenges of applying CPS in typical project workflows and open areas for research and development are also discussed in detail.

5.1.1 The State of Productivity in Construction

Today, the construction industry is still plagued with inefficiencies, including cost overruns and delays in execution of projects. The average productivity compound annual growth of US construction was negative while other industries such as manufacturing, oil and gas and other sectors were performing three times better than construction. According to KPMG's Global construction survey (Armstrong and Gilge 2017), only 25% of projects finished within 10% of their original schedule and only 31 percent of all projects completed within 10% of their budget in the past 3 years of common commercial and industrial building projects. While best practices such as the Last Planner System and lean construction principles do improve schedule and cost performance on construction sites, still 22% and 13% of projects where best practices are implemented exhibit schedule delays and cost overruns respectively (Beven and Jones, 2016).

The waste and variations also come from the utilization and productivity of the workers, equipment, and materials. Recent research indicates craftspeople spent an average of 52% of their work hours at the workface while only 34% they stayed for more 10 min which are considered as value-creating, and 50% of their time they were not at where the schedule shows. The workers have little control over their own productivity lost throughout the day, because of the material locations and plan changes.

The same report by KPMG (2016) shows that among various project controls metrics, companies consider adherence to the project schedule is the number one issue that they face in the execution of their projects. There is a myriad of factors that have contributed to the lack of growth in construction productivity and the complexity of executing projects on time and on budget. A careful examination of the most recent studies and reports including McKinsey & Company (Changali et al. 2015; Barbosa et al. 2017), KPMG Global Construction Survey (Armstrong and Gilge, 2017), ENR Dodge Data and Analytics (Beven and Jones, 2016), and internal anecdotal observations from more than 100 construction projects over the past 10 years that the Real-time and Automated Monitoring and Controls (RAAMAC) lab at the University of Illinois at Urbana-Champaign has been involved in, has revealed a list of issues as key contributors and the root-causes of lack of productivity in the construction industry: (a) Inadequate communications-inconsistencies in reporting of project plans and actual work in place makes it difficult for subcontractors, contractors, and owners to maintain a common understanding of how projects are progressing at any given time; (b) Flawed performance management – due to the lack of systematic and frequent communication and accountability in execution, the unresolved issues quickly stack up; (c) Poor short-term planning- construction firms are good at understanding and planning progress to be achieved in 2–3 month but rarely have an insight for next week or two; (d) missed connections to actual progress - the individuals involved in project planning or revising short-term and long-term plans are usually not working on construction sites; (e) Insufficient risk management- reliability and risk in short-term project plans are not systematically assessed; and (f) Poor decision-making-day-to-day planning and decision making is frequently inhibited due to poor communication surrounding daily work progress. In the next section, we discussed the opportunities of leveraging the growth of data in construction for progress monitoring.

5.1.2 The Unprecedented Growth of Data in Construction

Although the construction industry has been seen as one of the worst in terms of technology adoption rate, the collection of visual data throughout the construction process has grown exponentially in recent years. Onsite personnel collects daily photos to document the progress through smartphones and tablets and uses various applications to track issues and changes. The easy access to cameras and other technologies such as camera-equipped ground/aerial vehicles increases the number of images and videos gathered on construction site tremendously. Recent research shows that there are about 325,000 images are taken by professional photographers, 95,400 images by webcams, and 2000 images by construction project team members at a typical commercial building project (~750,000 sf). This trend of using visuals and sensor data to document construction progress provides a unique opportunity for CPS as inputs to keep the production status updated.

5.1.3 The Potential of CPS for Construction Progress Monitoring

Through the previous sections, reports and research indicate that waste and inefficiency occur in construction due to the failure of maintaining smooth communication. With the unprecedented growth of visual data as an input in the CPS, it could improve communication and establish a bidirectional feedback loop for construction progress monitoring. The visual data provide the Reality in the CPS to continuously update the current progress of construction. On the other hand, with the broad implementation of n-dimensional BIM (i.e. 3D models enriched with information such as time, cost, safety, and productivity), enhanced 3D visualization with semantic building information provides the Plan in CPS to compare against the Reality for progress verification. Different use cases have shown the value-added by utilizing BIM from early design phase to facility management, such as Lu et al. (2014) report 6.92% cost saving by using BIM, Staub-French and Khanzode (2007) report 25–30% productivity improvement by using BIM for coordination and constructability reviews to identify design conflicts. The integration of Reality (visual data collected onsite) with Plan (nD BIM) can efficiently communicate the necessary information for successful project control.

5.2 Review of Current State-of-the-Art CPS Technologies for Construction Progress Monitoring

CPS for construction progress monitoring can be divided into four key components: data collection, progress monitoring, activity monitoring and reporting. Over the past few years, researchers have been developing and validating new robotics, computer vision and predictive data analytics techniques for these components in the construction domain, and many of these have already been used in the industry. The following sections introduce the state-of-the-art CPS technologies in research and industry in terms of progress monitoring, we will discuss the fundamental theory behind the applications and the implementation of the real-world use cases.

5.2.1 Data Collection

The current practice of data collection is still relying on manual procedures of photo taking and video camera set up. The process is time consuming, costly and often does not guarantee the completeness of the capture. To address these challenges, recent studies have focused on automating the process through unmanned aerial and ground vehicles to acquire visual data (Ibrahim et al. 2017; Asadi et al. 2018; Ibrahim and Golparvar-Fard 2019). These systems often are equipped with multiple types of sensors and cameras and integrated with a computational platform that could perform autonomous navigation in a construction environment. The vehicle needs to collect data for progress monitoring and automatically navigate and map the environment at the same time. In this section, we will discuss the current technologies used in unmanned aerial and ground vehicles, and the optimization of the data collection process.

5.2.1.1 Autonomous Data Collection

Autonomous data collection is developed to provide the desired frequency of data collection and to ensure the completeness of the resulted 3D Reality models usually through unmanned aerial vehicles (UAVs) and ground vehicles/rovers/mobile robotic system. Because of the nature of the two platforms, UAVs are often used for exterior environment data collection and rovers are used for the interior environment data collection on construction sites. Although there is also a significant amount of research utilize UAVs for interior navigation and mapping, there is currently little adoption in construction due to safety concerns. The following sections discuss the applications of these two different types of robotic system in construction site.

Unmanned Aerial Vehicles Performing autonomous flight through UAVs in an exterior construction environment is relatively mature because of the well-developed GPS-based navigation technologies. With good reception of GPS, UAVs can perform autonomous flight through predefined flight plan according to the requirements and guidelines. Currently, there are multiple applications provide flight planning feature for users to plan the flight on the map before going to the actual construction site. To ensure the completeness of the resulted 3D Reality models, these tools usually require input for a minimum percentage of overlap between images. However, there are still several challenges regarding the completeness and efficiency of the flight plan: (1) flight plans are based on existing orthographic map that does not consider the complexity of the building structure; (2) risks associated with permanent and temporary structures are not considered; (3) flight plans only support 2D plans with]] specific patterns which do not capture the z-dimension of the structure and often results in Reality model without the views from sides; and (4) construction usually progress in specific areas significantly while other areas remain almost unchanged, current flight plan is not driven by changes of the construction.

To overcome these challenges, researchers utilize Reality data generated beforehand as a priori to create flight plans accordingly with a fixed safety distance to ensure the completeness of the results. 3D flight plans are also created using a bounding box around the target structure with a preset offset to maintain a safe distance to the target. BIM-driven visual quality metrics are developed to create flight plans that guarantee the completeness of Reality and quality of images for progress monitoring. Change-driven flight plans are also developed by using the 4D BIM as a priori to predefine the frequency and coverage for the construction site. Flight simulators are developed to ensure the safety and visibility of the UAVs. UAVs based Reality model evaluation is developed by synthesizing feature tracks using flight plans and BIM or Reality models to better control the variables during the actual flight.

Unmanned Ground Vehicles, Rovers, Mobile Robotic System Unlike UAVs, rovers are often deployed in an interior construction environment that is limited to GPS-based navigation. With limited computational resources on the platform, the real-time vision-based processing system can also only deal with relatively simple planning tasks. To overcome the challenges and support construction progress monitoring using rovers, autonomous navigation through onboard processing unit that can integrate multiple types of sensory and visual data is necessary. Simultaneous Localization and Mapping (SLAM) is used in robotics to create and update the map of an unknown environment while simultaneously identifying the location of itself in the map. To enable autonomous navigation, rovers obtain information from multiple types of sensory and cameras and process it using SLAM onboard to quickly localize images taken in the building and mapping the environment. Hector SLAM (Kohlbrecher et al. 2011, 2014), ORB SLAM (Mur-Artal et al. 2015) uses different sensory data such as 2D LiDAR sensor and monocular camera to build a navigation map. Although SLAM is well suited for construction interior mapping, it does suffer from with drift errors leading to misalignment of local maps and affect the navigation. Research uses Internal Measurement Unit (IMU) data and Extended Kalman Filtering (EKF) to improve the accuracy of localization and reduce the mapping errors (Einicke and White 1999). SLAM-related research in construction has focused on generating and registering point clouds in an efficient and inexpensive way (Jog et al. 2011; Brilakis et al. 2011a; Amer and Golparvar-Fard 2018), and autonomous navigation for construction progress monitoring(Jin et al. 2018; Kim et al. 2018c; Asadi et al. 2018). Several studies integrated BIM-driven path planning, Ultra-Wideband indoor positioning and other sensors as a mobile robotic navigation system for indoor construction applications. Other than autonomous data collection, recent research has also investigated methods to better distribute cameras and to analyze the best camera viewing angle for optimizing the data collection process. (Fig. 5.2)

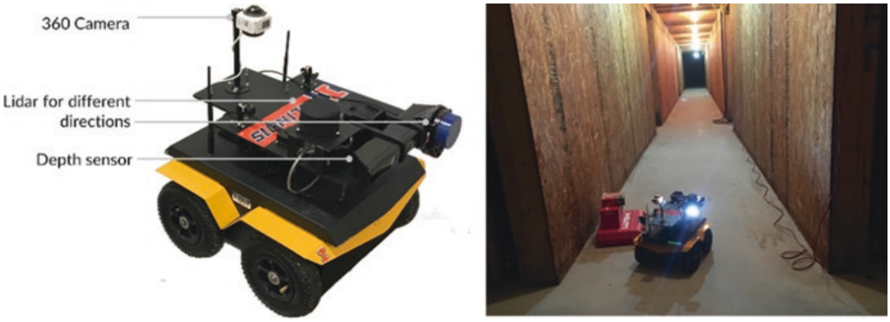

Fig. 5.2 An example of an autonomous rover settings and operating in construction site, the rover can navigate, map and analyze data in real-time automatically

5.2.1.2 Optimization of Existing Data Collection Process

Camera placement is critical to effectively monitor operation-level activity monitoring. Current strategies of placing fix cameras onsite are largely depending on the engineers' experience and surrounding environment restrictions (Kim et al. 2019). The problem of camera placement is similar to the well-studied art gallery problem, research has integrated construction-related variables and developed mathematical methods to optimize the numbers, locations, types, and orientations of the camera placement in construction sites. Research on cost and coverage optimization and BIM-driven indoor camera placement also shows the potential to monitor interior spaces. To streamline the data collection process for progress and activity monitoring, we have discussed the autonomous data collection and optimization of the existing process. In the next section, we will introduce state-of-the-art research in construction progress monitoring.

5.2.2 *Construction Progress Monitoring Techniques*

Current practices of construction progress monitoring still highly rely on site engineers conducting job walks to document the status and issues. While this process is labor-intensive, costly and subjective, research has developed methods that utilize reality capture techniques to obtain as-built status and compare to the 4D BIM for automated progress monitoring. Reality capture has also gained popularity in practice for construction progress monitoring by providing visual verification and measurement capability in recent years. In this section, we will review the latest research and commercial application on using reality capture for progress monitoring.

5.2.2.1 Reality Capture Techniques

Reality capture transforms real-world subjects such as buildings, site conditions, bridges into to digital model representation. This process results in 3D models that are formed by millions of points or meshes that are usually called point clouds or mesh models. Image-based 3D reconstruction and laser scanning are the two techniques that are widely used in practice. Image-based 3D reconstruction can take in all images taken from different sources on the construction site and generate the Reality model. It is currently used as one of the main documentation and project control tool. Laser scanning provides high accuracy results that could be used for quality control and assessment, but the process is relatively time-consuming and labor-intensive. These techniques provide site engineers with quick and accurate access to the current site conditions, where it has the potential to replace the traditional time-consuming site survey and daily job walks. Using Reality capture for progress monitoring.

Schedule task-level progress monitoring uses computer vision techniques to obtain the task status by analyzing the geometry and appearance of the corresponded task location in the Reality model. The task locations that are derived from Work Breakdown Structure (WBS), task names, task IDs, 2D drawings and 4D BIM are shown as an area in the images or volumes in the 3D point cloud models. To examine the state of progress of the task, the geometry and appearance of the task location in the Reality are then compared to the Plan to determine the status. Geometry is used to analyze the physical occupancy of the element, and appearance is used to examine the state of the task at the same location. Today, there are two dominant practices for leveraging images for tracking work in progress:

1. Generating large panoramic images of the site and superimposing these large-scale high-resolution images over existing maps (see Fig. 5.3) – While these images provide excellent visuals to ongoing operation, they lack 3D information to assist with area-based and volumetric-based measurements necessary for progress monitoring. Also, none of the current commercially available platforms provide a mechanism to communicate who is working on which tasks at what location and they mainly deliver high-quality maps of construction sites.

2. Producing 3D point cloud models–The state-of-the-art in image-based 3D modeling methods from computer vision domain has significantly advanced significantly over the past decade. These developments have led to several commercially available platforms that can automatically produce 3D point cloud models from collections of overlapping images.

In practice, today's several AEC/FM firms have started to utilize Reality models generated from images taken by UAVs to document progress and issues. However, to fully reach the potential of using Reality models, it needs to be integrated with 4D BIM models to streamline the process of project controls.

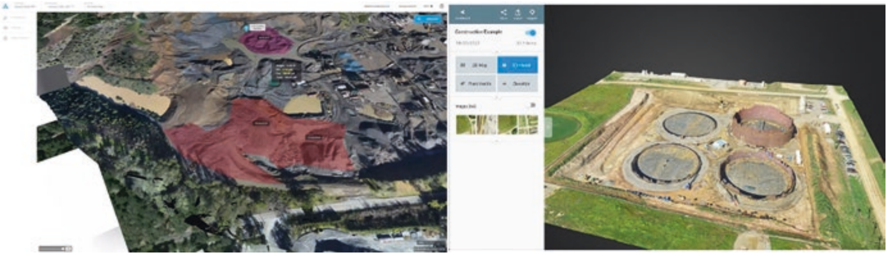

Fig. 5.3 DroneDeploy and Skycatch drone based visual data management platform – high-level top-down images are used to produce large-scale high resolution orthophotos and overlay them over existing maps. These images are also used to generate point cloud models

5.2.2.2 4D Reality Capture Integration With BIM

Point clouds generated from the typical Structure from Motion pipeline have arbitrary coordinate systems. Although the current 3D reconstruction process usually uses the GPS information from the image metadata, the output point clouds could still be up-to-scale due to missing or inaccurate information. Thus, their pixel units do not directly translate to real-world Cartesian coordinates. To register the point clouds in the world coordinate system, at least three points or correspondences with Ground Control Points or BIM are required. The three correspondences are used to solve for the similarity transformation between the two coordinate systems (Golparvar-Fard et al. 2009, 2012). These corresponded could be based on (1) setting visual surveying benchmarks with known real-world coordinate systems such that the user (manually or through an automated detection procedure) can establish their correspondence with site coordinates, or (2) manually finding correspondence between up-to-scale point clouds and BIM. Examples of GCP are shown in Fig. 5.4, where markers can be automatically or manually detected and their coordinates from the point cloud data can be matched to their equivalent from 4D BIM.

Several researchers have also focused on automating the process of alignment between BIM and point clouds without markers or GCPs. This especially becomes a difficult problem in built environments where structures and elements usually share similar geometry shape with symmetric characteristic. Previous works achieved limited automated registration with pre-defined constraints (Nahangi et al. 2015), semi-automated approaches (Bosché 2012), limited symmetric geometry identification or partial or pre-processed data (Son et al. 2015) and prior information assisted system (Bueno et al. 2018). While this research area remains open, general purposes such as progress monitoring can be satisfied with manual registration discussed above. With having the BIM model registered to point cloud model, progress information extraction and comparison of reality vs. plan are discussed in the next section.

Methods to Compare Reality Versus Plan Research on visual construction monitoring has focused on an automated comparison of 4D BIM with time-lapse videos,

Fig. 5.4 Example of GCPs (marked in red) place on the construction site for registering the Reality models to BIM or real-world coordinate system

or 3D image-based and laser scanning point clouds. These investigations are mainly focused on how the physical presence of building elements or their appearance can be detected. Much additional work in model-driven visual sensing is needed to bring these methods into an application. Also at best, these methods only tie performance deviations with retrospective Earned Value metrics and do not communicate who is working on what task in what location on a daily/hourly basis. Hence, a major time lag exists between facing an issue on-site once work is underway and when managers and other trades on the site are informed to mobilize teams into unoccupied locations, streamline workflows, and minimize waste. The inability to have two-way communication on task scope, methods and resources also delays work approvals, quality inspections, contractor hand-overs, and leads to waste.

The state-of-the-art methods of automated comparison are still in its infancy. Largely because these methods leverage the geometry of the 3D reconstructed scenes to reason about the presence of elements on the construction sites. As such, they are unable to differentiate operations details such as finished concrete surfaces vs. forming stage and cannot accurately report on the state of work-in-progress. On the other hand, methods that detect and classify construction material from 2D images have primarily been challenged in their performance due to their inability to reason about geometrical characteristics of their detected components.

Geometry-Based Progress Monitoring Image-based 3D point clouds are generated through an SfM-MVS pipeline and integrated with BIM model in Industry Foundation Classes (IFC) format to reason about the occupancy and visibility of the elements. A supervised machine learning method that utilizes Support Vector Machine (SVM) is developed to determine the state of progress (Golparvar-Fard et al., 2012). On the other hand, laser scanning point clouds of Mechanical Electrical Plumbing (MEP) system are compared against the BIM model to monitor progress for interior construction progress which has a lower tolerance of accuracy (Bosche et al. 2014). To effectively differentiate operation details of concrete activities such as formwork, rebar and concrete placement, research has developed methods to detect construction objects (Turkan et al. 2012). However, these methods are limited

Fig. 5.5 Progress is shown in as-built and 4D BIM models with color-coded status superimposed together (left) (Golparvar-Fard et al. 2012), laser scanned as-built (middle) and 4D BIM model (right) (Turkan et al. 2012)

in their ability to detect operational details and the occlusion and visibility of elements in the point clouds. (Fig. 5.5)

Appearance-Based Progress Monitoring To efficiently detect operation level progress of tasks located in the same place, appearance-based methods focus on using computer vision techniques to classify the material of the task location and integrate with geometry information to infer the progress status. For example, formwork and concrete placement activity occur at the same location but with a different appearance, as a result, occupancy-based method is unable to detect the difference while appearance-based method can detect the material. Research developed methods to backproject planned BIM element location to the corresponding image using the camera information from the 3D reconstruction process, and classify the construction material from the image patches (Han and Golparvar-Fard 2015). They further leverage the geometry feature of the image patches to enhance the accuracy of material recognition (Han et al. 2018). However, these methods are unable to utilize the geometrical characteristics of their detected components (Fig. 5.6).

Even though significant improvements are achieved in the past decade, to automatically detect the progress in full-scale projects within the CPS requires (1) accounting for the lack of details in 4D BIM, (2) addressing as-built visibility issues, (3) creating large-scale libraries of construction materials that could be used for appearance-based monitoring purposes; and (4) methods that can jointly leverage geometry, appearance, and interdependency information in BIM for monitoring purposes.

5.2.3 *Activity Analysis*

To detect activities and operation-level details, site engineers analyze the video footage from the fixed cameras manually and create a crew balance chart to understand productivity and safety. The process of manual examination is time-consuming, labor-intensive and expensive. Besides, the high per-hour cost of the heavy equipment and risk of struck-by accident when workers are on the site also draws

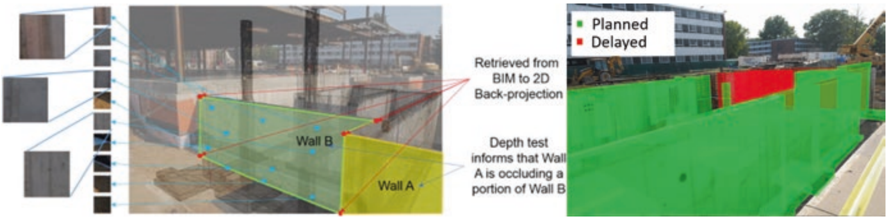

Fig. 5.6 Using patches retrieved from BIM to 2D back-projection to classify material and performing depth test to exclude occluding area (left); progress status is extracted by comparing as-built and as-planned after occupancy detection and material classification (right)

attention from construction researchers. Recent research used the latest computer vision techniques such as object detection, tracking and pose estimation, to analyze the activity of construction resources and monitor resource allocation and progress. The following section introduces the state-of-the-art computer vision techniques that are applied in the context of construction for activity analysis.

5.2.3.1 Computer Vision Techniques for Activity Monitoring

Activity analysis includes several computer vision tasks to successfully analyze a complete sequence of activities. The method needs to first identify the construction resource, track the pose of the object and further estimate the movement of the object. Each step is considered a challenging task for a computer to automatically perform (Szeliski 2011) because the occlusion, appearance, and poses of the object can vary in different environment settings. Traditional methods such as bag of words, brute force matching against large databases have been proven not reliable because of its high dependencies on the surrounding elements. Machine learning methods such as boosting, neural networks, SVM and recent deep learning approach have attracted more attention to address the challenges of activity analysis. To apply these detection methods to fixed cameras' video footage, it also involves object tracking from a sequence of video frames and pose prediction and association between frames.

Computer vision-based operation-level monitoring focuses on tracking the construction resources (workers, equipment and materials) and analyzing the interaction between each other via visual data collected on the construction site. Object detection and activity recognition techniques are applied on construction equipment and workers to track the trajectory and motion for measuring the input resources in each activity (Fig. 5.7). For equipment productivity analysis, single and multiple equipment activity recognition methods are developed to examine the earthmoving and dump truck efficiency (Golparvar-Fard et al. 2013; Kim et al. 2018b), then dirt loading cycling time is evaluated through the identified activity to improve productivity (Rezazadeh Azar et al. 2013). Point cloud volumetric measurement with video analysis for finer time scales productivity estimation are fused to analyze the

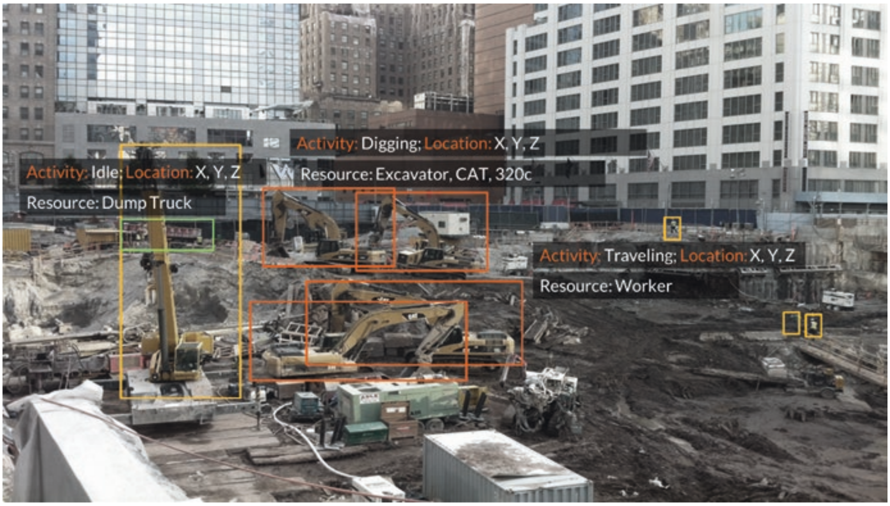

Fig. 5.7 Using the image sequence from a network of fix cameras, research developed methods that automatically detect the equipment, the activity and the locations. The output could be generated in the form of crew balance chart and used to improve the productivity

productivity onsite to the schedule task level (Bügler et al. 2017). These productivity data are also inputted into simulation models to better estimate task completion and project duration (Kim et al. 2018a). Besides equipment productivity analysis, pose estimation and worker detection method are also developed for work sampling automation and productivity assessment. To be able to train a machine learning method to detect worker's activity, researcher has developed a crowdsourcing web-based annotation tool to gather ground truth data efficiently (Liu and Golparvar-Fard 2015). Ironworker, carpenter activity are classified into 16 different types of activities for individual work through surveillance videos (Luo et al. 2018b). Activities are also recognized through the spatial and temporal relevance between workers and objects where 17 types of construction activities are recognized (Luo et al. 2018c, a). The majority of these works only track the location of the workers. However, without interpreting activities and purely based on location information, deriving meaningful workface data is challenging (Khosrowpour et al. 2014; Yang et al. 2015). For example, for drywall activities, distinguishing between idling, picking up gypsum boards, and cutting purely based on location is difficult, as the location of a worker would not necessarily change during these tasks.

However, computer vision methods are also not advanced enough to conduct detailed assessments from videos or RGB-D data because methods for fully automated detection and tracking (Brilakis et al. 2011b; Escorcia et al. 2012; Memarzadeh et al. 2013), and deriving activities from long sequences automatically (especially when workers interact with tools) are not mature (Gong et al. 2011; Golparvar-Fard et al. 2012; Khosrowpour et al. 2014). The current taxonomy of construction activities also does not enable "visual activity recognition" at a task level to be meaningful for workface assessment (Liu and Golparvar-Fard 2015). While full automation is appealing, training machine learning methods require very large amount of empirical data which is not yet available to the construction informatics community (Liu and Golparvar-Fard 2015).

The following section discusses the development of organizing the information analyzed from the data collection, progress and activity monitoring into construction language that can be used for project managers' project control decision making.

5.2.4 Construction Progress Monitoring Reporting

To organize the analyzed data into an actionable deliverable, reporting completes the last mile of the progress monitoring CPS. Reporting support decision making for proactive project control, visual verification for production tracking and progress documentation for various purposes such as billing and issue management. Research has developed a web-based system that color-code the Reality and Plan model according to the status; dashboards and reports that organize construction data into informative predictive metrics, charts and weekly work plan format; and daily construction reports that formalize the analyzed data into a company-specific format that could serve as billing and documentation purposes. In this section, we will discuss the background and applications of these reporting formats.

5.2.4.1 Color-Coded Reality and Plan Model

Construction practitioners have been using color-codes to present the progress of construction through different interfaces. Even in today's construction, it is common to find printed 2D drawings highlighted with different colors to communicate the current status of various locations (Fig. 5.8). Research has also been investigating using color-coded models to visualize the status, performance and risk (Golparvar-Fard et al. 2009; Han and Golparvar-Fard 2015; Lin and Golparvar-Fard 2018). Color-coded models are often used during coordination as a visual aid to facilitate communication. Several examples show that using a color-coded model is easier to visually communicate the issues and identify potential risk. For example, the façade of complex high-rise buildings usually involves several trades working in parallel on top of each other. This becomes a major coordination task for project managers to coordinate the sequence and safety between subcontractors. Without the use of color-coded models, it is hard to visualize at what time which subcontractor is working at what location. With the color-coded models, each subcontractor is represented as one color, and the 4D model highlights the BIM elements of the responsible contractor with its color as the timeline moves. This representation could facilitate the communication and planning regarding sequencing, resource management and logistics in coordination meetings so that issues are found beforehand, and the plan can be adjusted accordingly in real-time. Status visualization of

Fig. 5.8 Examples of printed 2D drawings with highlighted progress to communicate the actual status, this process is time-consuming and labor intensive

delay and on schedule is also used during the daily huddles on the construction site. Superintendents review the progress of each subcontractor through the 4D BIM model during the meeting daily huddles and adjust the tasks accordingly. Risk visualization of locations is useful during schedule meetings to identify the potential delays based on location and discuss the action plans circling the location from the models. With research showing much progress on visualization, color-coded models is also provided by construction software such as Navisworks and Synchro for various purposes such as 4D BIM simulation, delay and trade location visualization, Earned Value Analysis. Whereas color-coded visualization is helpful for coordination and planning, construction infographic dashboards and reports can quickly provide project managers and other stakeholders a grasp of the project status.

5.2.4.2 Construction Infographic Dashboards and Reports

Infographics provide an overview of the project status intuitively. Project managers usually prefer a higher level of information that could numerically and visually summarize project performance. Different metrics and charts are accordingly developed to indicate the status of projects. Among various metrics for progress monitoring, Percent Plan Complete (PPC) are widely used to track the ratio between the actual completed tasks to the planned committed tasks. PPC is easy to understand and allows project managers to quickly examine the reliability of the short-term plan retroactively over time. Coupling the PPC with the root-cause analysis enables indirect production flow tracking to improve the short-term plan in a weekly cycle. However, PPC does not capture the production flow directly and the numbers could be deceiving as it only reflects the progress on the short-term plan without connecting it to the master schedule (Sacks et al. 2017), for example, the PPC could be 80–90% for the week, but the overall project progress is behind schedule. To address the shortcomings of PPC, research developed Task Anticipated, Task Made Ready (TMR) (Hamzeh et al. 2012), Construction Flow Index (Sacks et al. 2017) and Task

Readiness, Readiness Reliability (Lin and Golparvar-Fard 2018) to proactively measure risk and reliability of the plan.

In practice, traditional construction management metrics such as the Schedule Performance Index (SPI) and Cost Performance Index (CPI) from Earned Value Analysis (EVA) is broadly used to monitor progress and cash flow. However, it is still retroactively measuring and predicting progress with mainly deriving the criticality of tasks from cost. This results in undermining the level of effort for the actual progress. In addition, it is often hard to direct the tasks from the schedule to the work packages that are used for cost estimation. Project managers end up estimating the budgeted cost for the EVA.

Currently, the above-mentioned metrics are all used to generate infographics and presented in a form of dashboards and reports. Usually this metrics are tracked in a weekly basis and used to create a trend line to provide the users a glance of the project status overtime. Metrics are also calculated based on task and shown in a weekly work plan format. Several commercial software provides interactive dashboards that provides user better understanding of the project performance. In the CPS for progress monitoring, the dashboards and reports and generated using the data collected on the construction site in real time, and provide direct feedback from the downstream of the production.

5.2.4.3 Daily Construction Reports

General contractors often monitor subcontractors' performance based on the actual progress that is reported in the daily construction reports (DCRs). General contractors receive DCRs from each subcontractor daily and summarized it into one internal report to document the overall project status (Fig. 5.9). These reports are the progress summary of the reported day and include information such as weather, subcontractor's name, trade type, worker's level of experience, manhour, number of onsite equipment, safety issues and the description and location of work. Currently, these DCRs serve as progress documentation for schedule improvement and records in a legal proceeding. These reports contain information that could support and defend delays and material costs due to change clause, constructive changes, work suspension, sequence changes or disruptions. It keeps a progress document that has been agreed upon by all project stakeholders. Whereas the main purpose currently is to document the progress, the potential of using these data for risk management of schedule, subcontractor billing and cost estimation have not been fully explored. These data are valuable and could be used to improve planning, coordination, and communication.

The DCR generation process is currently supported by commercially available software and general contractor's in-house software. However, the inefficiency and inaccuracy of the data collection still affect the quality and reliability of the DCRs. CPS could streamline the process from data collection to DCR generation with an autonomous process. With different sources of autonomous data collection, the Reality is captured and generated in the form of visual production model with 4D

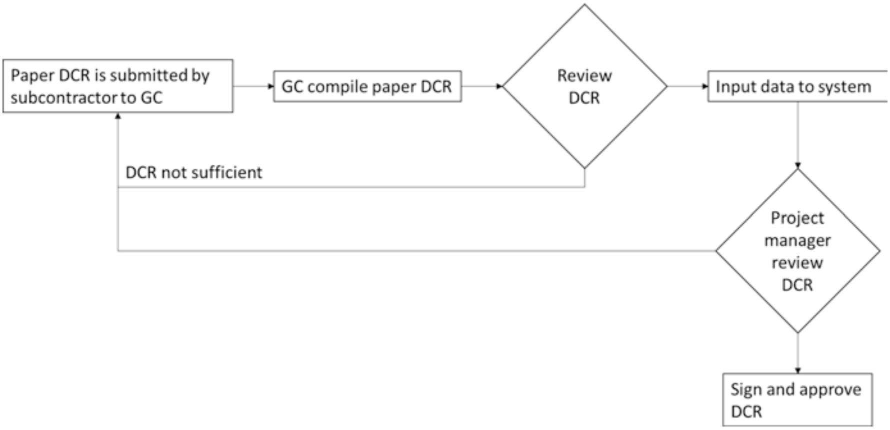

Fig. 5.9 The process of generating DCR to track daily progress on the construction site

Reality and BIM, the required DCR progress data are then automatically output in required format with the manhour, equipment, crew balance and related information organized based on work breakdown structure.

5.3 Opportunities, Challenges and Limitations for CPS in Construction Progress Monitoring

With the recent development in applying robotics and computer vision in construction and the exponential growth of visual data collected on the construction site, each component of the CPS for progress monitoring has improved significantly to support the automated process. Through the previous sections, we see substantial achievements have been made over the past decades, yet still, many problems remain as open research challenges. In the following section, the problems of each CPS component are discussed, and possible solutions are introduced.

The autonomous data collection process is still not well developed for construction progress monitoring purposes. The data collection process can be a lengthy but non-trivial work depending on the size of construction. The optimization of the data collection process has not been fully investigated. The current data collection process does not fully utilize the existence of 4D BIM, and focus on navigating and mapping based on the input from Reality. 4D BIM provides the planned changes that should happen in the future and could be used as a priori to optimize the data collection path. On the other note, coordinating multiple vehicles for data collection could be another way to facilitate the collection process of large construction space.

After the data collection, although recent algorithm improvement on image-based and video-based 3D reconstruction has shown promising results, the accuracy and completeness of the point cloud can still be improved on generating consistent good results in different environmental settings. For example, the reconstruction tends to produce poor quality results on reflective surfaces and thinner structures which are commonly seen in construction as curtain walls and steel components. On the other hand, geometry-based progress monitoring only provides binary results of the observed object. With the recent development in deep learning, integrating appearance-based methods that extract colors, texture, shape and semantic information from the 2D image can streamline the automated progress monitoring process. This further brings up the need for a complete construction material database that could be used for progress monitoring. For activity analysis, current research is also limited to the labeled data size. Today's research on equipment productivity analysis is still limited to a few machines such as dump trucks, crane, loaders, excavators, and workers. The data size needs to be expanded to fully support comprehensive activity analysis with a dynamic and realistic data source. There is also limited research on linking the input (equipment utilization and man-hours) analyzed from activity analysis with the output (progress changes) analyzed geometry and appearance-based method to examine the budgeted productivity rates.

Reporting is rather mature compared to the other three components. However, research has been developing complicated and specialized metrics for specific workflows. Generalized metrics that could apply to different workflows are more practical to implement across projects. Generalized metrics provide a common ground for comparing different projects and obtain more insights. For example, PPC is only applicable for projects that follow lean principles where it is not feasible for the critical path method (CPM) schedule projects.

The following section introduces the latest application of CPS for construction progress monitoring, implementation details and practical feedback from construction practitioners are discussed.

5.4 Case Studies

A complete CPS framework for progress monitoring is implemented and evaluated through a case study using a web-based visual production management system (Lin and Golparvar-Fard 2018). The data collection component of the CPS is performed by drone and rover to gather progress images at different times and locations. The system takes in the images and automatically generate 4D Reality with localized unordered images in the same environment. The 4D Plan model is created in the system by linking the look-ahead schedule to the BIM according to the work breakdown structure. The visual production model that integrates the Reality and Plan is used to compare and analyze the schedule deviation for progress monitoring with productivity input from the site engineers using the mobile application. This visual production model is used during the construction to provide "who does what work in what location" and the state of progress through the color-coded model and Reality model with images. The risk analysis based on the progress and productivity is provided weekly to help project managers better understand the reliability of the plan and tap off potential delays proactively. Daily construction and productivity

Fig. 5.10 The visual production management system in the CPS has been used on different construction site during the coordination meetings, it has been proved that it can efficiently enhance planning coordination and communication, and the reports provide insights for decision making

report are generated automatically to document the progress with verification from Reality. The system leverage the CPS to communicate progress efficiently for project control decisions, and enhance the process of planning, coordination, and planning. (Fig. 5.10)

5.5 Conclusions

We introduced the state-of-the-art research and applications of the four key components -data collection, automated progress monitoring, activity analysis, and reporting- in CPS for construction progress monitoring. The current development of CPS has shown promising results but the automation of each of the components and the integration between each other remains challenging with many open research problems such as optimization for automated data collection, integration of geometry and appearance-based progress monitoring, creating comprehensive datasets in dynamic environments. We provide a case study that illustrates the potential of CPS for construction progress monitoring using visual production models to improve planning, coordination, and communication.

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Chapter 6
CPS-Based Approach to Improve Management of Heavy Construction Projects

Nazila Roofigari-Esfahan and Saiedeh Razavi

6.1 Introduction

Over the last few decades and years after other industries, automated and integrated systems are becoming a part of construction processes. The main goal of employing such systems in construction is to fill the gap between project design and actual construction on site. This gap was found to be the main reason behind construction projects being behind schedule and/or over-budget (Repass et al. 2000, Anumba 1996). In order to achieve this goal, proper means should be provided to integrate all project components including project documents and information, actual construction processes on site and project management systems and technologies. Real-time communication is also another requirement of such a system. Such an integration and communication offers significant potential for better collaboration and coordination in construction projects (Akanmu, 2012). Cyber-Physical Systems are physical and engineered systems, whose operations are monitored, coordinated, controlled and integrated by a computing and communication core (Lee, 2008; Krogh et al., 2008; Rajkumar et al., 2010; Karsai and Sztipanovits, 2008; Suh, 2014). The main features of CPS systems include (Li et al., 2009; Shi et al., 2011; Kim and Kumar, 2012):

- Closely integrated: Generation of CPS requires tight integration between computation and physical processes.
- Cyber capability in every physical component: The computation processes are embedded in every physical component.

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- Networked at multiple and extreme scales: CPSs are distributed systems including various networks.
- Complexity: The dynamics of CPSs is complex, involving the stochastic nature of communication systems, dynamics of computing systems, and continuous dynamics of control systems.
- Dynamically re-organizing/reconfiguring: Such versatile and complex systems require highly adaptive capabilities.
- High degrees of Automation: As a result of the high level of embedded interaction between components and the need to real-time actions to be taken based on retrieved information, CPSs require automatic advanced feedback control technologies to enhance the automatic data transfer between all components.

In an environment, as data intensive as construction, Cyber-Physical systems (CPS) can be developed for managing extensive amount of information and leveraging the interconnectivity of construction components and processes. This will help construction projects to move towards intelligent, resilient and self-adaptable systems; systems that are able to monitor and adapt themselves through feedback loops according to the context for which they are designed.

This chapter presents an application of the Cyber Physical Systems-based approach for enhancing real-time bi-directional progress monitoring and control of highway and road projects. The goal of the proposed CPS application is to enable deployment of integrated computational and physical systems in the construction phase of roadway projects. To this end, the method makes use of Earned Value (EV) monitoring method and Raspberry Pi microprocessors. The application and significance of each of the CPS layers in the proposed control and monitoring application is discussed to improve future outcomes. A proof of concept case study is presented to demonstrate the efficacy of the proposed CPS approach.

6.2 CPS-Based Approach for Progress Monitoring and Control of Highway Projects: Earned Value Management Using Raspberry Pi

A CPS application is presented here to enhance project control in road and highway construction. Raspberry pi, a simple micro-processor, equipped with different modules is used to retrieve the required progress information, perform calculation and analysis and to transfer them to the cyber space of the system. A web server is used to host the cyber space; to store the retrieved information and to transfer the results back to the construction site through the Raspberry Pi. Figure 6.1 schematically demonstrates the network diagram of the proposed application.

Highway and road construction projects selected for this study are characterized by their sequential, repetitive, and inter-related activities. In these projects, construction crews are often required to repeat the same work in various locations and therefore, frequently move from one location to another. The frequent movement

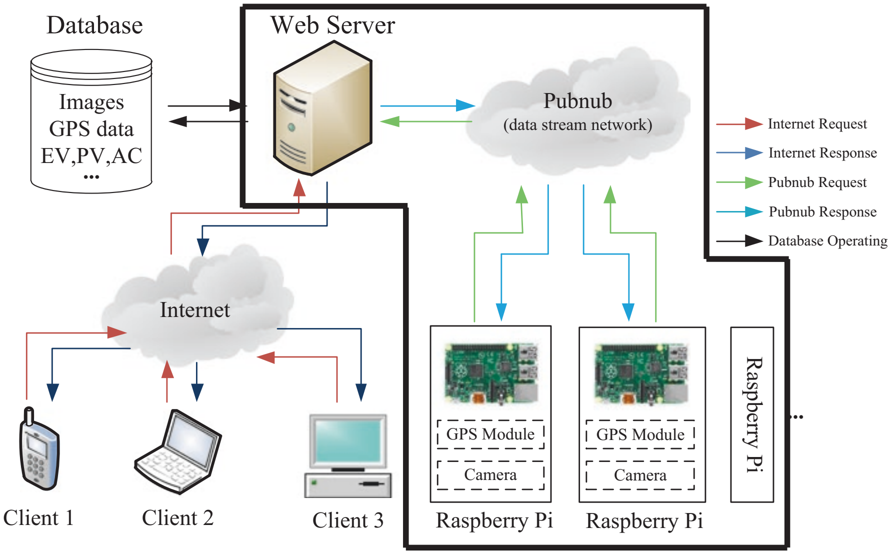


Fig. 6.1 Network diagram of the proposed application

and one dimensional type of progress of these projects makes it possible to use the movement of the resources of activities as a measure of the progress of the corresponding activity (Roofigari-Esfahan et al. 2015). Also, the activities of these projects are extremely inter-related. Thus, delays can potentially extend the overall project schedule beyond the anticipated completion date. Consequently, it is important not only to continuously integrate the movement of resources into their progress monitoring and control systems, but also to reflect any change in the schedule of the activities on the job site to make necessary adjustments. The application proposed here tends to fulfill these demands by establishing bi-directional data transfer for control and monitoring of highway projects. Figure 6.1 demonstrates the general data transfer flow of the proposed application. The details of components of the proposed CPS-based application follow.

6.2.1 Physical Layer

The physical layer of the proposed application consists of all the physical components required for tracking the progress of highway activities. The moving resources, i.e. equipment, play an important role in this framework as their movement while carrying out and activity, e.g. asphalting, is used as a means of retrieving the necessary information regarding the progress of the activity. The availability of non-moving resources of an activity which are mainly the materials designed and ordered for performing that activity can also be tracked to ascertain the activity can be proceeded at each moment in time.

Due to the fact that progress of highway project activities is dependent upon the movement of its resources, the most important data to be retrieved is the continuous locational and speed data of the equipment or workers executing the activity. Furthermore, time-lapse progress images can provide a visual sense of the activity's progress over time. Raspberry Pi equipped with different sensing modules is another physical component of this framework that is used not only to continuously retrieve progress data, but also to use this data in the computation/control layer to extract the required monitoring and control information and to transfer data between cyber and physical spaces.

6.2.1.1 Sensing

Raspberry Pi 2 Model B equipped with GPS, cellular and camera modules were used as the primary sensing device. Such sensing device is capable of real-time project data acquisition, processing and analysis as well as transferring progress information to the cloud server and receiving information or instruction. GPS and camera modules are used for capturing location and project images and the mini cellular GSM module is utilized to communicate this data to the cloud server/cyber layer in real-time. In such system, a piece of equipment performing a critical activity, e.g. asphalt paver, is equipped with this sensing device. Figure 6.2 illustrates the sensing device assembled for this study.

It should be noted that the accuracy of the GPS module is approximately 1.5 m for lower speeds on jobsites (2–10 km/h) and 3 m for higher speeds on roads and highways. The cellular module transmits the locational data along with the calculated distances and speeds to the server every five seconds. The progress images are also taken and sent to the server every five minutes. A GPS antenna is also added to aid in receiving the satellite signals and make the module usable in low signal environments. This data is used by the Raspberry Pi to automatically update the progress information on the server and website accordingly. In addition, two indicator LEDs are added to the device to represent the status of the GPS and the Internet connection as well as to inform the personnel and workers on site of changes/updates in the computational/control layer in real-time. The continuous green light is representative of presence of internet connection and GPS signal respectively, while continuous red light is representative of connection lost. Similarly, flashing red light on the GPS indicator LED is representative of data transmission to the server while flashing red light on the internet indicator LED is representative of changes on the website.

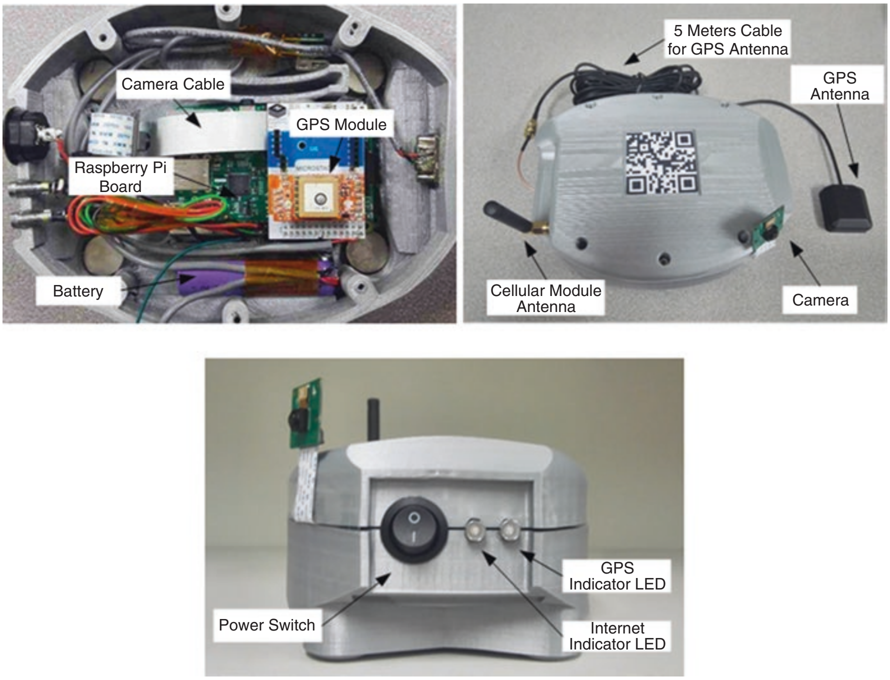


Fig. 6.2 The sensing device using Raspberry Pi

6.2.1.2 Raspberry Pi Micro Processor

Raspberry Pi is a credit card–sized mini-computer developed in the UK in 2012 with the intention of promoting the teaching of basic computer science in schools. Since its introduction, it has been applied in other sectors because of its customizable nature. The invention of these small size personal computers has caused a new revolution in the IT industry. There are several advantages in using these small inexpensive computers in tracking of construction processes and to use them as an integral part of any CPS application in Construction. These advantages include:

- Cost: Despite being as small as the size of a credit card, Raspberry Pi works as a normal computer at a relatively low price. Compared to other mobile devices such as cellphones and tablets, Raspberry Pi is offering much more with much lower price.
- Computational capabilities: The Raspberry Pi’s computational resources are equal to the average desktop or laptop, therefore suitable for high-performance computing. This surely makes Raspberry Pi a good alternative for being used in embedded systems where computation needs to be embedded in each component.
- Expansion capabilities: There are numerous modules available to expand the Raspberry Pi’s capabilities; all at very affordable prices. Everything from an I/O

boards (GPIO) to cameras and different sensors and cellular modules can be added based on the application. There are also a number of status lights available to Raspberry Pis that can be used to report on the status of different sensors. Opposite to cellphones and other mobile technologies that are bounded to their specifications and are costly to adapt in order to achieve needed specs, expansions to the Raspberry Pi are selected based on the required accuracy and can be changed as required at very low cost.

- Control actuation: Raspberry Pi can send control signals with its onboard pins. This makes it achievable to drive motors, power switches, and others in the physical layer. Compared with cellphones, tablets and other mobile devices, the onboard pins of Raspberry Pi not only make it easy to acquire information from different sensors but also help to execute the commands sent from the cyber layer.
- Small form factor: The Raspberry Pi (with a case) can be held in one's hand. This means the Raspberry Pi can be integrated inside of devices and attached to different equipment without adding any weight. Next generation of Raspberry Pis are expected to be even smaller than the one used in this study.
- Multiple uses: Having the storage on an SD card makes it easy to swap with other SD cards running other GNU/Linux distributions to quickly and easily change the functionality of the Raspberry Pi.
- Energy consumption: The energy consumption of a Raspberry Pi with different expansions is much less than other mobile devices. As a result, different batteries can be used to charge the Raspberry Pi according to the application, with an average 6–15 hours of continuous use to one week of standby status; which is enough for this application in construction.

All the advantages stated above makes Raspberry Pi a good alternative for other mobile technologies currently used in construction including cellphones, tablets, etc.

6.2.1.3 Computational and Control Layer

The computational/control layer is responsible for monitoring the progress data received from the construction site, carrying out the required calculations and evaluations and transferring back the results to the physical components through actuation or to the application layer through API. The data flow in computational and control layer is showed in Fig. 6.3.

A web server is used to host the database that is used to store the retrieved data and the website designed to be used as user interface (as described later in the application layer). Accordingly, the web server continuously receives the sensed locational data from the physical components through Raspberry Pi and stores it in the database. The data transmitted includes not only the raw locational information and images, but also the calculated progress information by the Raspberry Pi itself, as Raspberry Pi is also an active component of this layer; including total traveled distance from the beginning of the day (the progress of the activity), travel distance

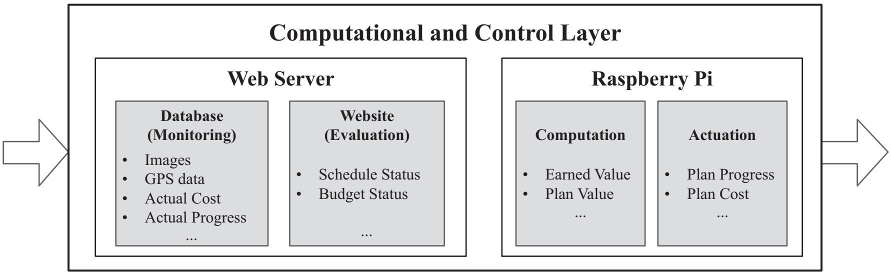


Fig. 6.3 Computational and control layer for highway projects

between each two check times, the speed of the equipment and the earned value calculations based on the actual progress.

6.2.1.4 Monitoring

The aim of the monitoring phase of the computation/control layer is to oversee the locational data retrieved from resources through the sensing process to evaluate the progress of activities. This accordingly paves the way for performing Earned Value calculations (using Eqs. 6.1, 6.2, 6.3 and 6.4). The network provides the means for bi-directional communication between Raspberry Pis attached to the resources, the server and the application website. The Raspberry Pi is constantly connected to the server through cellular network and transmits and receives data to/from it. The Web site is also designed as a user interface to enable demonstration of the acquired progress data and EV monitoring and additionally enable user data update input to modify the calculations in real-time based on the most recent project design/schedule/budget. This is elaborated in more detail in the application layer.

6.2.1.5 Computation: Earned Value Management of Highway Projects

Earned Value Method (EV) is the most commonly used method for project control in the construction industry. It provides an early warning of performance problems when properly applied. The EV method is usually used for cost and schedule control because it combines technical performance, schedule performance, and cost performance within a single framework (El-Omari and Moselhi 2011). Contractors typically state a clear preference for EV progress tracking over object oriented quantity (progress) tracking for buildings and industrial facilities. As a result, integrating this well-accepted and commonly used technique with the CPS approach will facilitate timely control of the project and progress analysis. In the EV method, project progress is evaluated in an objective manner using three measures (Rose 2013) as shown in Fig. 6.4:

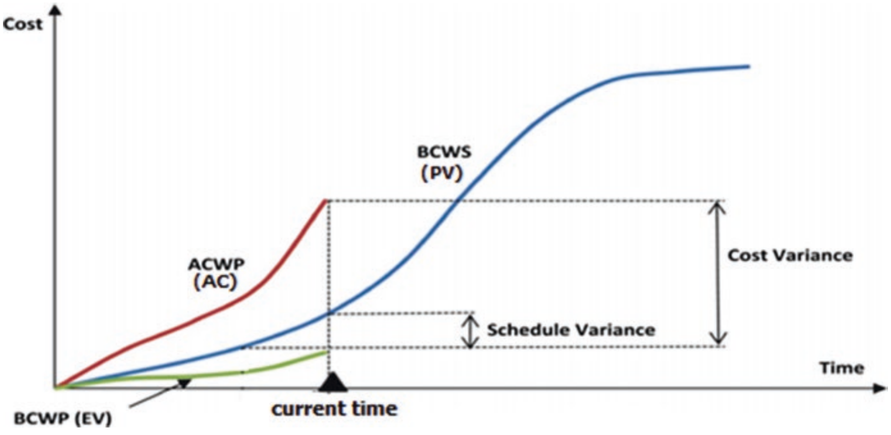


Fig. 6.4 Earned value measurements

Budgeted cost of work scheduled (BCWS): measures the work that is planned to be completed in terms of the budgeted cost.

Budgeted cost of work performed (BCWP) or EV: measures the work that has actually been accomplished to date in terms of the budgeted cost.

Actual cost of work performed (ACWP): measures the work that has been accomplished to date in terms of the actual cost.

The significance of these three values is that they distinguish the schedule and cost performances of the project at successive reporting periods. The following performance indicators are calculated based on these three values:

Cost variance (CV): CV=BCWP−ACWP, with CV > 0 indicating cost savings;

Schedule variance (SV): SV=BCWP−BCWS, with SV > 0 indicating schedule advantage;

Cost Performance Index CPI: CPI=BCWP/ACWP, with CPI > 1.0 indicating cost savings; and

Schedule Performance Index (SPI): SPI=BCWP/BCWS, with SPI > 1.0 indicating schedule advantage.

As stated earlier, in highways and road projects, the movement of certain resources while on work can be considered as a measure of progress of the associated activity (Roofigari-Esfahan et al. 2015). As a result, the EV calculations are adjusted here based on the distance paved by the resources. These adjusted equations are then used to update EV measurements on the site in real-time.

$$\text{Planned Progress} = \frac{\text{Planned kilometers}}{\text{Total activity kilometers}} \tag{6.1}$$

$$\text{Actual Progress} = \frac{\text{Actual kilometers}}{\text{Total activity kilometers}} \tag{6.2}$$

$$\mathrm{PV} = \text{Planned value} = \frac{\sum_{i=1}^{n} \text{Planned kilometers} \times \text{Planned cost}}{\sum_{i=1}^{n} \text{Total activity kilometers}} \tag{6.3}$$

$$\mathrm{EV} = \text{Earned value} = \frac{\sum_{i=1}^{n} \text{actual kilometers} \times \text{Planned cost}}{\sum_{i=1}^{n} \text{Total activity kilometers}} \tag{6.4}$$

$$\mathrm{AC} = \text{Actual cost} = \sum_{i=1}^{n} \text{actual kilometers} \times \text{Actual cost} \tag{6.5}$$

The earned values are updated continuously according to the data received. This, however, is not enough and in order to create the bi-directional data communication, the system needs to be able to accept input from the project management team and to apply their changes/suggestions in the calculations in real-time. Respectively, the main purpose of the application layer is to concede such data entry/update and to bounce this information back to the computation phase for updating calculations as discussed in the application layer.

The result is demonstrated on the web site as performance indicator; i.e. whether the project is ahead/behind schedule and or under/over budget. Such result is representative of the project status and accordingly informs the user about whether the project is under/over budget and ahead/behind schedule based on the progress monitored from the beginning of the activity/project to the end of that day.

6.2.1.6 Actuation

The actuation or the control component of this layer is achieved by using the Pubnub Network (data stream network) as demonstrated through the black region in Fig. 6.1. The main advantage of Pubnub Network is enabling real-time communication between the website and Raspberry Pi without knowing the IP addresses of both sides. After all the necessary calculation has been performed in the computation phase, the actuation allows reflecting decisions and/or changes in the plans. This is carried out through the actuation phase which uses the Raspberry Pi as well. In any of these cases, the changes are automatically notified on the Raspberry Pi through status lights. The user then is able to retrieve the changed information through scanning the barcode designed for the Raspberry Pi (as shown in Fig. 6.2), which automatically directs him/her to the website where changes are visible.

The control component is designed to allow user input to make sure the Earned Value calculations are carried out based on the most recent project information. These inputs include but are not limited to any change in the planned schedule/budget for the project/activity and the actual costs occurred to date. The changes in the planned data could be resulted from late delivery of material, weather/site conditions, changes in service/material pricing, change orders, etc. The actual cost also needs to be updated based on the costs actually occurred on a daily basis. As shown in Fig. 6.1, any change in these control parameters is sent to Raspberry Pi in real-time, and then the corresponding calculation is changed. In addition, the preferred numbers of progress photos that are required to be shown in the website can also be entered.

6.2.1.7 Database

In order to achieve the real-time realization of the project status as described in the previous sections, a dynamic connection is required between the website and the database. The architecture of operation database is shown in Fig. 6.5. All the images, GPS data, calculated parameters are uploaded in the database which will provide corresponding information upon the request received from the designed website.

To store the images, they are Base64 encoded in Raspberry Pi using Python language. By sending the HTTP request to database, the connection between Raspberry Pi and database is established. The encoded images are sent to the database using their ImageID and corresponding ImageData. The encoded data is then decoded in the website, and displayed. The GPS and calculation parameters are also stored separately in the database as shown in Fig. 6.6.

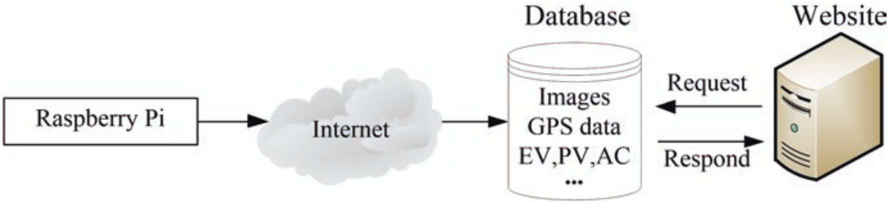
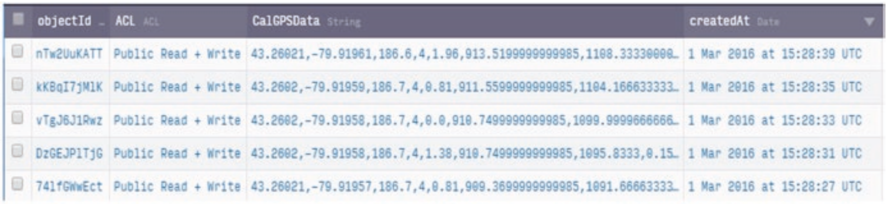
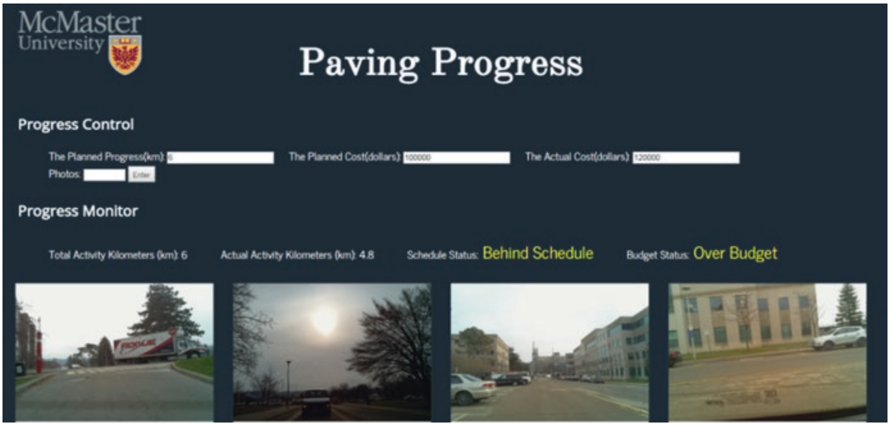


Fig. 6.5 Data transfer schema



☐	objectId	ACL	CalGPSData	createdAt
☐	nTw2UuKATT	Public Read + Write	43.26021,-79.91961,186.6,4,1.96,913.5199999999985,1108.33330000…	1 Mar 2016 at 15:28:39 UTC
☐	kKBqI7jMlK	Public Read + Write	43.2602,-79.91959,186.7,4,0.81,911.5599999999985,1104.16663333…	1 Mar 2016 at 15:28:35 UTC
☐	vTgJ6J1Rwz	Public Read + Write	43.2602,-79.91958,186.7,4,0.0,910.7499999999985,1099.9999666666…	1 Mar 2016 at 15:28:33 UTC
☐	DzGEJPlTjG	Public Read + Write	43.2602,-79.91958,186.7,4,1.38,910.7499999999985,1095.8333,0.15…	1 Mar 2016 at 15:28:31 UTC
☐	741fGWwEct	Public Read + Write	43.26021,-79.91957,186.7,4,0.81,909.3699999999985,1091.66663333…	1 Mar 2016 at 15:28:27 UTC

Fig. 6.6 Storage of GPS Data and Calculated Parameters in the Database



The Planned Progress(km): 6
The Planned Cost(dollars): 100000
The Actual Cost(dollars): 120000
Photos:

Total Activity Kilometers (km): 6
Actual Activity Kilometers (km): 4.8
Schedule Status: Behind Schedule
Budget Status: Over Budget

Fig. 6.7 Generated application website

6.2.1.8 Application Layer

The main purpose of the application layer is to provide an interface for demonstrating the actual progress on the site to the user, project management team and other project participants in this case, and to let data entry/update from the user in real-time. For this purpose, a website was designed using JavaScript. The website is connected to the server and the database. As a result, each data entry/update automatically is sent back to the computation phase to update calculations. Furthermore, any input/change in the website is simultaneously transferred to the Raspberry Pi and accordingly indicated on the job site through the status lights (LEDs). Figure 6.7 illustrates a snapshot of the designed website.

As shown in Fig. 6.7, there are three main components in the website: progress control (control phase), progress monitoring (monitoring phase) and visual progress view. In addition to the control and monitoring parameters, the progress on site is visually demonstrated on the web site through different figures. The time-lapse images of each day are used to generate a video of the construction progress in that day. The updated Earned Value plots can be generated at the end of each day or at any time during the day by downloading the progress information that is stored in the database in real time. For this purpose, a MATLAB code is written to decode the stored data and to generate Earned Value plots up to the time data is downloaded.

6.3 Case Study

The field experiment aims to demonstrate the applicability and feasibility of the developed system for real applications. For this purpose, three scenarios were designed and carried out, to facilitate evaluation of different components pertinent to real-time bi-directional earned value management of road and highway projects. To this end, a vehicle was utilized and was driven on arterial roads of McMaster University's Campus to simulate asphalt paving activity. The equipment was driven with low speed (approximately 2 km/hr) comparable to real construction condition. The experiment was carried out in two consecutive days and the real-time progress information was collected.

In order to carry out Earned Value calculations, the initial planned measures need to be known. Assumed initial measures include: the total of three kilometers is planned to be asphalted in 2 days, four working hours per day, total cost is $100,000 per day and is assumed to be distributed linearly over the 1.5 km progress planned for each day. In order to retrieve real-time information of activity progress including location and site images, the Raspberry Pi was mounted on the back of the vehicle. Different data transfer intervals of five seconds and five minutes were selected to send retrieved data of the location and progress images using the cellular module. The locational coordinates (longitude, latitude and altitude) of the vehicle retrieved through GPS module, is received and used to calculate travel distance, total distance, and earned value, schedule and cost variances in real-time. The raw and calculated locational data is send to the database every 5 seconds, to be stored and presented on the website accordingly. The status of the project is estimated using the schedule and cost variances and is shown on the website as ahead/behind schedule and under/over budget (see Fig. 6.8). The progress images taken are also stored in the database and updated on the website every 5 min as shown in Fig. 6.7.

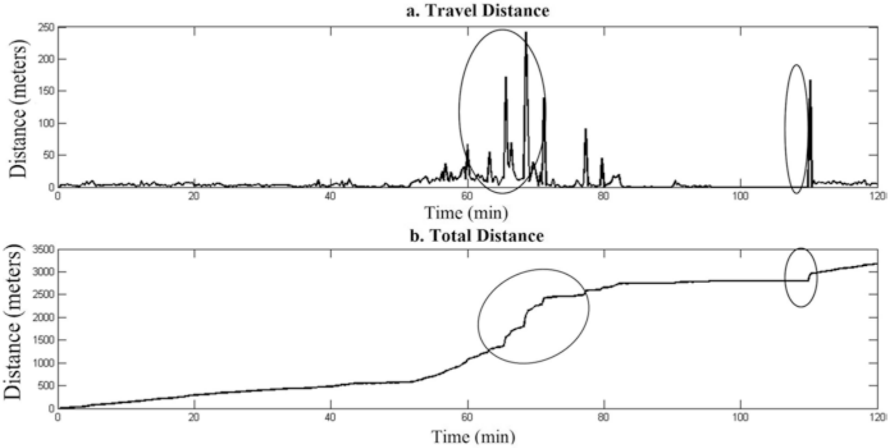


Fig. 6.8 (**a**) Real-Time travel distance and (**b**) Total distance paved for scenario 1

Three scenarios were set up within 8 hours' experiment; first, two hours' experiment was carried out to investigate effects of changes in speed of the equipment in accurate real-time data collection. The next four hours' experiment was performed in two consecutive days, two hours each day to examine continuous data collection and how the tracked performance was compared to the plan. The last experiment was performed with the aim to examine the bi-directional real-time data communication of the application as described in detail in the following sections.

6.3.1 Scenario 1

In order to examine the accuracy of the collected data and its relevance to the speed of the equipment and data communication, the experiment was done for two hours with different speeds ranging from 0 (complete stops for a period of time) to 15 km/h. the results are shown in Fig. 6.8. It was found that the developed framework is able to realize the varied movement patterns of the equipment good accuracy. As it is shown in Fig. 6.8(b), the vehicle had two complete stops between minutes 42–50 and 85–110. Although the variation in travel distance in each 5 sec interval is well demonstrated, the accuracy of detected distance is less on higher speeds i.e. where higher slope is demonstrated in Fig. 6.8(b). In speeds comparable to construction paving speeds, the detected travel distance is within 1–2 meters accuracy. Also, in areas with less cellular network strength, the data transmission might take between 5–10 seconds and consequently, the measured travel distance would appear to be more than the actual as shown in Fig. 6.8(a).

As stated earlier, earned value calculations was also performed in real-time on the Raspberry Pi and was sent to the database along with the raw locational data (see Fig. 6.9). The respective Earned Value charts were generated afterwards from the data stored on the database for each scenario; comparing planned values at each point in time with the actually achieved progress. As anticipated, the earned progress was more than planned as the average speed was higher than the plan. As a result, the status of the project was reported as ahead of schedule and over budget on the website.

6.3.2 Scenario 2

The second scenario was carried out in two days, two hours each day, to examine efficacy of the proposed framework in continuous real-time earned value monitoring of the road and highway projects. As a result, the speed was selected to be

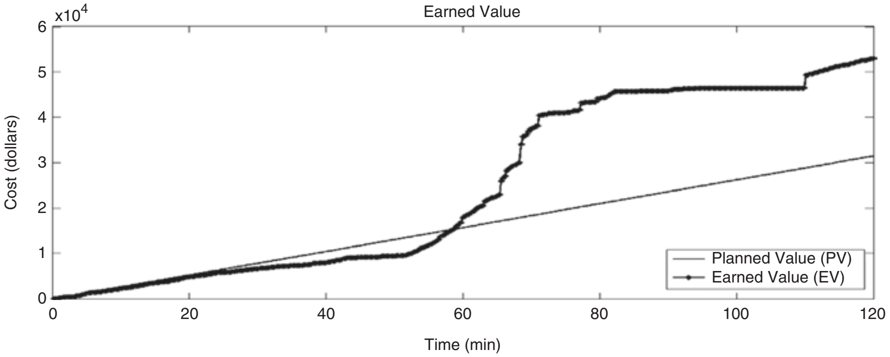


Fig. 6.9 Earned value for scenario 1

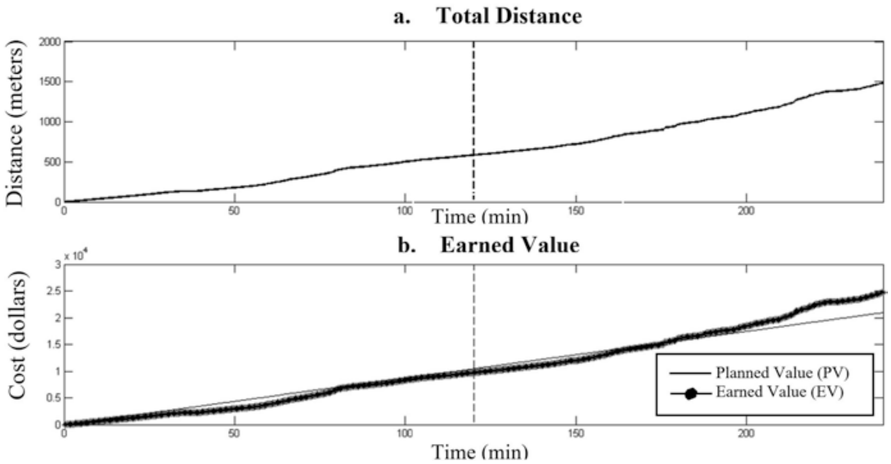


Fig. 6.10 (**a**) Real-Time total distance and (**b**) Earned value for scenario 2

constant with average of 1.5–2 km/h. As demonstrated on Fig. 6.10, the total paved distance (Fig. 6.10(a)) and earned value (Fig. 6.10(b)) curves were smooth and with small variations from planned. Total of 1.5 kilometers was paved which is according to the plan. As a result, this scenario was finished on time and budget, which was demonstrated on the website.

6.3.3 Scenario 3

The last scenario was carried out to examine the important real-time bi-directional data communication between the website and the jobsite. Although the one-way real-time data communication (from construction site to the website and as a result to the project office) was examined through the first two scenarios, the bi-directional communication should exist as preliminary requirement for a Cyber-Physical system in this context. For this purpose, the third scenario was designed to examine the capability of the proposed application in real-time communication from website to the job site. In this scenario, the value of planned progress and planned cost were changed (and stated by authorized users on the website) while the activity was undergoing on the jobsite. As a result, the updated planned information was communicated to the Raspberry Pi on the jobsite and was used to calculate the rest of the calculations.

In order to examine this capability, first, the project planned cost was changed from $100,000/day to $120,000/day half way through the experiment. As a result, the updated calculations of Eqs. 6.1, 6.2, 6.3, 6.4 and 6.5 were undertaken using the updated value and therefore a jump appeared in the real-time tracked earned value as well as on the planned value curve. The planned project cost then was reduced from $120,000 per day to $90,000 per day and immediate changes appeared on both planned value and earned value curves as shown in Fig. 6.11(b). In addition, less progress (approximately half kilometer) was achieved in this scenario as seen in Fig. 6.11(a). As a result, the scenario was reported behind schedule and over budget.

The scenarios demonstrated promising results in putting in place real-time bi-directional communication between the physical and cyber worlds of such example. The real-time earned value generated for each scenario also effectively illustrates the progress on site, calling for just in time corrective actions when necessary.

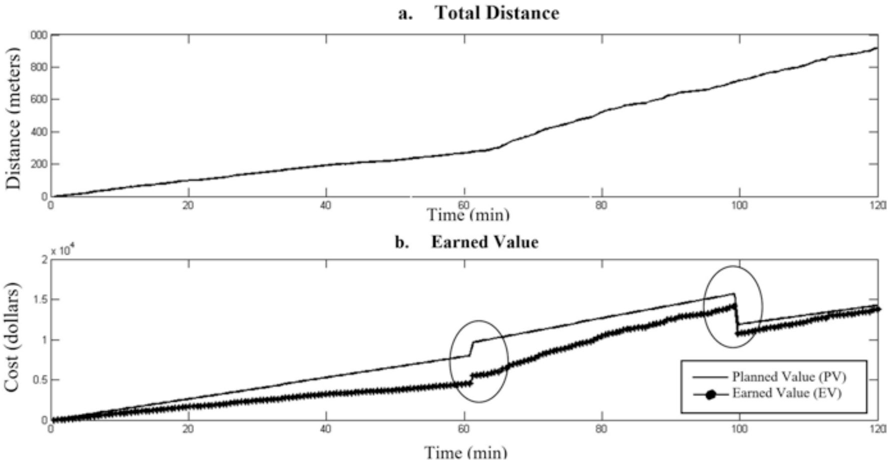


Fig. 6.11 Real-Time (**a**) Total distance and (**b**) Real-time earned value

6.3.4 Concluding Remarks, Challenges and Future Directions

The generated CPS-based system tends to minimize the need for reconfiguration and reprogramming of the computational processes as it is based on adaptive interaction of computation/control processes with the physical construction processes and components. An application of the proposed framework in improving progress monitoring and control of highway projects using Earned Value Method is also presented. The case study proves that employing the CPS bi-directional data communication can enhance construction progress monitoring and control by allowing real-time feedback loops and enabling right-on-the-spot corrective actions. It also facilitates the communication between the construction site personnel and various project parties as they are all involved in the generation of the up-to-date information in real-time. The case study at this stage is designed to track one activity on the jobsite to demonstrate the efficacy of the proposed application. Future advancements of this framework will consider more than one activity to also take into account relationships between activities and their interaction.

Further, the construction sites are frequently encountering different conditions which make them fall behind schedule/over budget and are always a place for claims and disputes. For example, construction sites are often affected by different environmental conditions including extreme weather, humidity, etc.; which correspondingly affect their performance, subsequently impacting project monitoring and control. These conditions can also be communicated in real-time, decreasing the amount of disputes. Moreover, such conditions can be retrieved and integrated to the framework through different sensors, practically showing their effects on the project performance.

There is a considerable potential for a Cyber-Physical systems approach in enhancing the existing smart systems and applications in construction projects. However, similar to any other ground-breaking technology, bringing CPS approach to the construction industry which is slow to adopt technology would carry a number of challenges. The uncertainty and lag from a real-time physical system to discrete-time digital control is an obstacle that must be overcome. Synchronization within the system and over-complexity are also obstacles that must be taken into consideration in order for the CPS to be applied to construction processes. Processing of the intensive data collected from the physical construction processes and the required interoperability between all physical and computational components of the system are other key challenges that need to be addressed to efficiently set up the integrated system. As it is demonstrated through a sample application in this research, overcoming these challenges opens infinite potentials for use of CPS to enhance different construction processes and facilitate real-time management throughout the life cycle of construction projects.

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Chapter 7
Cyber-Physical Systems for Temporary Structures Monitoring

Xiao Yuan and Chimay J. Anumba

7.1 Introduction

The past few decades have seen a high record of structural failure related to temporary structures (i.e. scaffolding, temporary support system, and formwork system). As a result, around 100 deaths, 4500 injuries, and cost of \$90 million occur every year due to the improper management of temporary structures. While about three quarters of construction workers in the United States work on or near temporary structures, inadequate attention has been paid to the safety management of temporary structures. The advanced benefits of information and communications technologies, such as Cyber-Physical Systems (CPS), provide promising solution for advanced monitoring of temporary structures. In particular, CPS enables real-time and remote control of temporary structures performance for safety management purpose. This chapter reviews the most common types of temporary structures and their associated problems, and discusses the design of a CPS based prototype system for temporary structures monitoring. The developed prototype system was evaluated through experimental tests and an evaluation workshop. Finally, it discusses the practical deployment considerations and trajectories for future research.

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7.2 Overview of Temporary Structures

Temporary structures refer to the system or structures, which provide temporary support to the work during construction, as well as the structures used temporarily for a short period. The first category of temporary structures is usually found on construction jobsites, which provides support or enables permanent works (Grant and Pallett 2012). Examples of these temporary structures include earthwork sheeting & shoring, temporary bracing, soil backfill for underground walls, formwork systems, scaffolding, and underpinning of foundations. The other type of temporary structures, which is designed to be used temporarily, includes temporary or emergency shelters, temporary grandstands, lighting support structures for public events, and indoor and outdoor theatrical stages (Parfitt 2009).

Improper monitoring of temporary structures has caused a large number of accidents over the past few decades. For example, in 1987, a section of the University of Washington football stadium expansion collapsed because of premature removal of temporary guy wires. In 1998, a major scaffold system on a 49-story building in New York's Times Square collapsed due to the improper bracing removal, with one person killed, several injured and hundreds displaced from their residences. In 2019, a scaffolding system in Brooklyn, New York collapsed under high winds, resulting in at least three people injured.

Increasing public attention has been drawn due to the frequent structural failures of temporary structures, yet few regulations or standards have been in place to prevent temporary structural hazards. This section provides an overview of the common types of temporary structures and conventional practices of temporary structures management.

7.2.1 Common Types of Temporary Structures

Temporary structures can be generally divided into six categories in general. These include earthwork shoring/sheeting systems, temporary bracing systems, underpinning of foundations, scaffolding systems, formwork, and temporary performance stages. For better understanding of each type of temporary structure, the definition, key features, and potential causes to structural failures of each the temporary structures are summarized as follows.

7.2.1.1 Earthwork Shoring/Sheeting System

The earthwork shoring/sheeting system usually include steel soldier piles, sheet piles, and slurry walls used during the excavation of earth. The shoring/sheeting system is primarily used for the prevention of soil movement and cave-ins. In

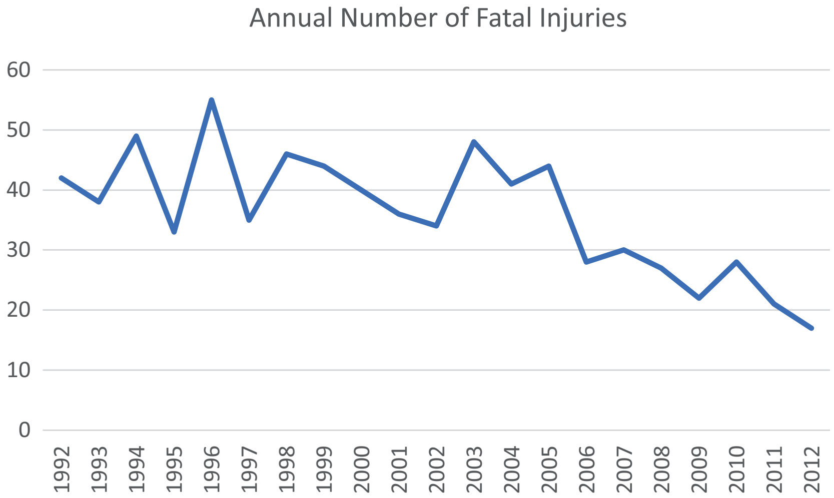


Fig. 7.1 Fatal occupational injuries due to cave-in, from 1992 to 2012 (BLS 2007, 2012)

addition, it also helps to minimize the excavation area and prevent potential settlements of the nearby buildings.

Although the shoring/sheeting system is commonly used for safety purpose during the excavation of earth, earthwork has become a substantial risk for workers due to the inappropriate design and installation of earthwork shoring & sheeting systems. In spite of the decreasing amount of cave-in accidents over the past decade, there has been an annual average of 20 cave-in accidents since 2006. Please refer to Fig. 7.1 for the number of fatal injuries due to cave-in accidents from 1992 to 2012 (BLS 2007, 2012).

The structural failure of shoring/sheeting system can be caused by three major factors: (1) the lack of shoring/ sheeting system; (2) inadequate shoring/sheeting system; (3) overloading from external load during the work of excavation.

7.2.1.2 Temporary Bracing System

Temporary bracing systems are systems used to enhance the stability of a structure or used temporarily before the installation of a permanent bracing or before the component is capable of self-supporting. The temporary bracing systems are widely used during the construction of masonry walls, tilt-up precast concrete panels, steel frames, large timber framed walls, and wood trusses. For example, the temporary cross-bracing system is used to improve structural stability during the construction of wood frame. The temporary bracing system used during the excavation include both internal bracing and tie backs.

During the process of construction, the whole structure being built relies heavily upon the temporary bracing system before the permanent bracing system is in place. According to Feld and Carper (1996), most of the structures collapse during construction due to instability issues often caused by the insufficient support of temporary bracing system when external load was applied (Delatte and Rens 2002). As a result, inappropriate use of temporary bracing systems has been identified as one of the four most common reasons for structural steel failures during construction (Kaminetzky and Carper 1992). Besides, the specific use and inspection of temporary bracing system often rely upon construction workers, who may have no experience or qualification for structural performance analysis (Feld and Carper 1996).

Temporary bracing structural failures are mainly driven by the following three factors: (1) unexpected natural hazards (Delatte and Rens 2002), (2) insufficient or nonexistent bracing system (Kaminetzky and Carper 1992), and (3) imbalanced loading due to construction sequence (Feld and Carper 1996). According to Delatte and Rens (2002), construction workers, who may not be qualified in identifying the safe sequence, primarily determine the sequence of installing temporary bracing system and construction work.

7.2.1.3 Underpinning of Foundations

The underpinning of foundations provides support for additional depth or bearing capacity of an existing foundation. It is commonly used when: (1) a structure with deeper foundation is to be built close to an existing building, (2) prevention of foundation settlement of an existing building is needed, (3) the service purpose of a structure is changed, and (4) basement below an existing building is added (Ratay 1996).

Structural damage of adjacent structures has been observed frequently due to underpinning of foundations (Peraza 2007). As a result, inappropriate management of underpinning of foundations may cause injuries, loss of life, property loss, and construction delay (Peraza 2008).

There are five main causes of structural accidents related to underpinning of foundations, including: (1) lack of underpinning, (2) inadequate underpinning, (3) over excavation, (4) impact from rubble foundation (Peraza 2006), and (5) impact from soil and groundwater (SEAoNY 2005).

7.2.1.4 Scaffolding System

A scaffolding system usually consists of tubes, couplers and boards, and is commonly used on the construction jobsite during erection, maintenance, access or inspection of building systems. Scaffolding systems have been utilized as temporary working platforms for construction workers for the past 5000 years (Grant and Pallett 2012).

According to analysis by Whitaker et al. (2003), the five most common root causes to the collapse of scaffolds are: (1) improper ties of scaffolding system to buildings, (2) insufficient bracing within the scaffold structure, (3) overloading with building material (Ayub 2010), (4) subsidence of foundations of scaffolding system, and (5) inadequate supervision of structural performance of scaffolding system.

7.2.1.5 Formwork

Formwork is the system used for poured-in-place concrete construction. It supports concrete curing at the construction jobsite or for precast sections at a factory. Increasing use of formwork has caused serious safety issues (Shapira 1999). As a result, formwork construction has caused frequent injuries and illnesses (Hallowell and Gambatese 2009). For example, among the formwork related injuries, 5.83% of the falls and 21.2% of struck accidents occurred due to the construction of formwork (Huang and Hinze 2003). Jannadi and Assaf (1998) have identified the preparation of formwork as a dangerous stage. Besides, Hadipriono and Wang (1986) have identified the two most dangerous stages of formwork system as: (1) during the pouring of concrete and (2) during the removal of formwork and post concrete curing.

Based on the 85 cases of formwork system collapses over 23 years, Hadipriono and Wang (1986) identified seven major causes to formwork systems failures, including (1) improper/premature removal of formwork (Feld and Carper 1996), (2) inadequate design of formwork system, (3) improper shoring of formwork, (4) defective component, (5) improper connection of the formwork components, (6) insufficiently strong foundation, and (7) lack of inspection of formwork during concreting.

7.2.1.6 Temporary Performance Stages

According to Wainscott (2011), temporary performance stages are the structures used temporarily for outdoor performance over a short period (less than 90 days annually). There has been collapse of temporary performance stages for the past decades. For example, two temporary performance stages in the northeast Oklahoma collapsed in 2008 under severe wind. In 2009, the temporary performance stage of Big Valley Jamboree in Toronto collapsed with one killed and more than seventy individuals injured. Additionally, the Indiana State Fair Grandstand collapsed in 2011, causing multiple fatalities and at least fifty individuals injured. In 2012, the Downsview Park in Toronto collapsed with one person killed and three others injured. More recently, a stage roof collapsed in North Carolina in 2013 due to unexpected weather.

Past accidents indicate three major driving factors to the structural failures of temporary performance stages: (1) poor structural capability of components, (2) insufficient structural connection, and (3) the lack of engineering review after the stage is erected.

7.2.2 Conventional Prevention of Temporary Structural Hazards

In view of the frequent accidents due to temporary structural failures, the government and the industry have made efforts to address the safety issues related to temporary structures. These efforts include government regulations and standards, industry practice, and safety education program. However, there still exist temporary structures that are not covered by any of these safety practices. In this section, we provide a brief summary of the conventional prevention practice for temporary structures. The limitations of these existing efforts are also discussed.

7.2.2.1 Regulations & Standards

Current regulations and standards cover the six types of temporary structures: including earthwork shoring/sheeting system, temporary bracing system, underpinning of foundations, scaffolding system, formwork system, and temporary performance stages. The specific regulations and standards for each type of temporary structure are summarized as follows:

- Earthwork shoring/ sheeting system: OSHA requirements on earthwork cover the following four parts: (1) Supportive system of construction workers. OSHA requires that the supportive system should be installed during the excavation unless the excavation in conducted entirely in stable rock; (2) Soil classification. The determination of soil type should follow a specified soil classification method; (3) Design of shoring/sheeting system. OSHA requires a registered professional engineering for the design of shoring/sheeting system when the excavation is deeper than 20 feet. A required minimum demission of shoring components is provided by OSHA as a supporting guidance in designing a shoring system; (4) Excavation less than 200 feet in depth: a graphic summary of requirements is provided of OSHA under this situation.
- Temporary bracing system: Temporary bracing system is only covered by a few regulations with very brief descriptions. For example, the Code of Federal Regulations (CFR 1926.706(b)) requires “adequate bracing” by the temporary bracing system for masonry walls. However, no instruction has been offered for the assessment of an “adequate” brace. Similarly, the International Building Code (IBC) requires that the installation of temporary bracing system should be inspected whether it is installed as designed when the steel/ wood truss spans more than 60 feet. Yet there is a lack of detailed instruction on the measurement criteria, when and how frequently the inspection should be performed.
- Underpinning of foundations: there are only a few local states regulations on the underpinning of foundations. Even with these local regulations, the requirement on underpinning of foundation is very brief. Take the New York City for example; while controlled inspection is required, there is no detailed instruction on how to control it during the construction process.

- Scaffolding system: OSHA have several regulation requirement of scaffolding system, which cover the following areas: (1) design of scaffolding system: it is required that the scaffold should be designed by a qualified person; (2) construction of scaffolding system: OSHA requires that the construction of scaffolding system should follow the design; (3) scaffolding capacity: according to OSHA, the maximum load that can be applied to the scaffold system should be identified clearly; (4) scaffold platform: OSHA requires that the scaffold platform should be fully planked for safety purpose; (6) other requirements: there are also regulations by OSHA covering supported and suspension scaffold, access to the scaffold, use of scaffold, fall protection, and falling object protection from the scaffold system.
- Formwork system: The formwork should be designed, built, and maintained appropriately according to OSHA requirement. At the design stage, a qualified designer should perform it; during the use of formwork system, the formwork should be inspected by a qualified engineer for the entire process of concreate placement. It is required that the formwork should not be removed until the concrete is capable of supporting enough capacity as designed; as for the maintenance, the shoring equipment is required to be reinforced immediately once found to be weak or damaged;
- Temporary performance stages: few standards or regulations can be found for the temporary performance stages. Except for a few local requirements (such as New York local requirement), there has been a lack of national regulation on safety construction and maintenance of temporary performance stages for decades.

7.2.2.2 Industry Practices

To supplement the safety regulation and standards on temporary structures, industry practices on temporary structures have been published by industry associations, such as Mason Contractors Association of America (MCAA). For example, the Standard Practice for Bracing Masonry Walls under Construction published by MCAA provides instructions on the design of temporary bracing systems. It also specifies the restricted zone where work should not be performed once the wind speed reaches the prescribed threshold. Another example is the guideline on the design, manufacturing, and maintenance of temporary stage roofs by the International Building Code (2006).

7.2.2.3 Safety Training and Education

It is required by OSHA that employer should provide certain safety training to the employees. This helps to get workers educated about potential hazards and appropriate reactions under dangerous situation. In addition to the mandatory safety-training program, several safety-training resources published by OSHA and local governments are also available online to the public. These training resources cover the safety training on excavation, fall protection, scaffolding, concreate, and masonry. However, few training resources ca4r4n be found for the underpinning of foundations, temporary bracing, and temporary performance stages.

7.2.2.4 Limitations of Conventional Methods

All the safety regulations, practices and training programs discussed above have contributed to the decreased rate of construction structural accidents. However, there are still several safety related issues to be addressed according to Huang and Hinze (2006). For example, there is still a lack of safety regulation on some temporary structures, such as indoor and outdoor performance stages (Mckiniley 2011). Furthermore, temporary structures failures cannot be fully prevented even with enough safety regulations. This is because construction workers usually work under high pressure which makes it difficult for them to make appropriate judgement or to work with caution (Fabiano et al. 2008). While the use of Personal Protective Equipment (PPE) offers great protection to reduce the degree of injury, this is often treated as a passive method of protection, which cannot prevent or avoid the structural hazards.

In addition to the conventional practice, researchers (Kim et al. 2011; Zhang et al. 2015) have explored the prevention of temporary structural failure with the help of Information Technology (IT). However, current research efforts only aim at improving safety design and plan of temporary structures, which may fail to provide protection as expected due to the dynamic working environment on construction jobsite. Even with the real-time inspection of temporary structures (Moon et al. 2012), the structural hazards prevention is limited due to the lack of active interaction between the inspection system and the temporary structures.

In summary, conventional prevention of temporary structures, including regulations, industry practice, safety-training program, and research practices have benefited the safety management of temporary structure. However, more advanced and active control of temporary structures is needed. IT-based methods offer potential benefits to address the existing safety issues related to temporary structures.

7.3 Applicability of CPS to Temporary Structures Monitoring

CPS is generally realized through several supporting technologies so that the physical structure and its virtual model are integrated in some way (Akanmu et al. 2014). While little or no work has been done on CPS application in the area of temporary structure monitoring, there have been applications of CPS supporting technologies (including Building Information Modeling (BIM) and Data Acquisition (DAQ) system) for enhanced monitoring of temporary structures. In this section, a brief review of the concurrent application of CPS supporting technologies to temporary structures is summarized for better understanding of CPS applicability to temporary structures monitoring.

7.3.1 Use of BIM for Temporary Structures Management

As early as 2008, Li et al. have proposed the integration of design and construction of temporary structures through virtual prototyping. In 2012, BIM has been utilized by Chi et al. (2012) to develop 3D models of temporary structures for better visualization. In addition to visualization, design, construction and safety information will also be embedded into the BIM object of temporary structures as reference information to other parties. Zhang et al. (2015) developed a safety-rule based BIM for temporary structures to identify potential fall hazards automatically during the design stage. Instead of focusing on visualization and embedded information, Kim et al. (2011) introduced a safety identification system for temporary structures. Based on the simulation of construction schedule and location of temporary structures. BIM is also used by Kim et al. (2014) to identify appropriate temporary structures to be shared among projects for cost saving purposes. In general, all of these efforts have benefited safety planning and management of temporary structures through BIM technology.

7.3.2 Use of Data Acquisition System (DAQ) for Temporary Structures Management

A DAQ system refers to computer-based systems with digital input and output (UEI 2006). As information related to construction failures can be obtained through DAQ system, it has been increasingly used for temporary structures management (Moon et al. 2012). Examples of DAQ system application for temporary structures management include the use of Radio Frequency Identification, RFID (Yabuki and Oyama 2007), wireless sensor networks (Moon et al. 2012), and videos (Jung 2014). With the wide application of DAQ, more comprehensive structural analysis can be achieved for temporary structures monitoring.

The applications of CPS enabling technologies (such as BIM and DAQ) discussed above have highlighted the potential benefits and opportunities for CPS applications to temporary structures monitoring. Details of potential areas for CPS application in temporary structures are discussed in the following section.

7.3.3 Potential Areas for CPS Applications in Temporary Structures

Based on the overview of temporary structures and current application of CPS enabling technologies, there are two main potential areas that are in urgent need of enhanced management (such as the use of CPS): including temporary performance stages and temporary support systems.

Temporary Performance Stages While temporary performance stages have collapsed frequently over the past decades, few standards or regulations have come into effect to prevent potential structural failure of temporary performance stages (McKiniley 2011).

Temporary Support Systems The temporary support systems include four major types of structures: scaffolding system, earthworks, formwork, and temporary bracing systems. They are typically used as temporary safety access for construction workers on the construction jobsite. Among these temporary support systems, around eight workers get hurt each month due to structural failures of scaffolding systems on construction jobsites in the United States.

In summary, the frequent structural failures and lack of appropriate regulation of temporary structures require a proactive monitoring system, such as CPS, to provide for real-time monitoring of temporary structures (Yuan et al. 2016). Current applications of CPS enabling technologies (such as BIM and DAQ system) as reviewed above have highlighted potential applicability of CPS to enhanced temporary structures monitoring.

7.4 Design of Temporary Structures Monitoring (TSM) System

To explore CPS applicability to temporary structures, a CPS-based prototype system (named TSM) has been designed and developed. This section presents the TSM system architecture and discussed seven key system elements.

7.4.1 Overview of TSM System Architecture

The TSM system is designed such that both physical structures and their virtual models are integrated through a CPS bridge, where information is exchanged. Therefore, the system architecture of TSM consists of three major parts: the physical component, the virtual model, and the CPS bridge (see Fig. 7.2). Details of each component of the TSM system architecture are discussed below.

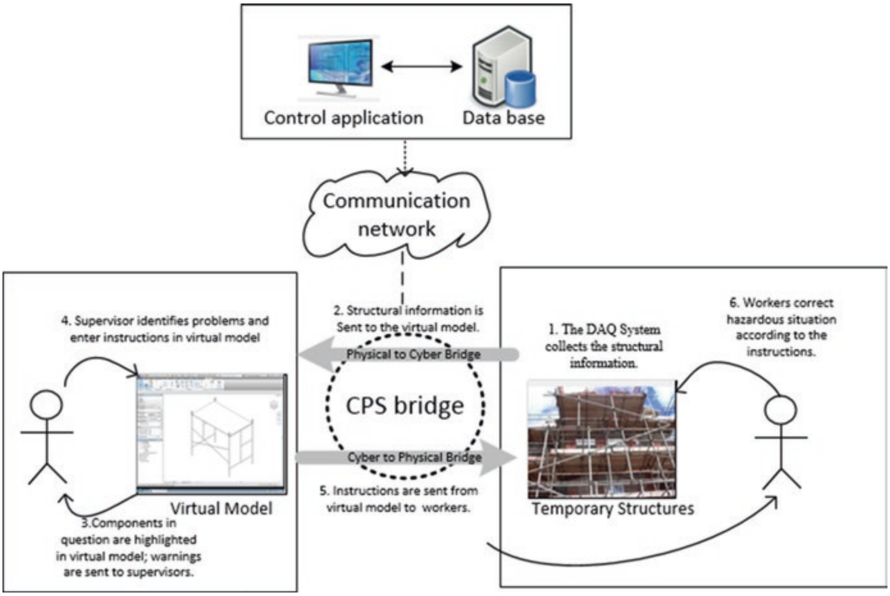


Fig. 7.2 System architecture of CPS-based TSM

Physical Component the physical components are the temporary structures discussed in the section on "Overview of Temporary Structures", including scaffolding systems, formwork and temporary performance stages.

Virtual Component the virtual component is the virtual model of the temporary structures, which supports visualization of the temporary structure's performance.

CPS Bridge the bridge between Cyber and Physical components includes bi-directional information flows: (1) Physical-to-Cyber Bridge, which supports the information flow from a physical structure to its virtual representation; (2) Cyber-to-Physical Bridge, which enables the supervision and control of a physical structure through its virtual model.

7.4.2 *Key System Elements*

As discussed above about TSM system architecture, the TSM integrates physical and virtual world through CPS bridge. The system architecture of TSM discussed above can be further broken into seven key system elements as follows.

- DAQ System: as a computer-based system with both input and output interaction (UEI 2006), the DAQ system has been frequently used as an important technology to prevent construction failures (Moon et al. 2012). In terms of temporary structures monitoring, DAQ supports the digital signal transmission between the physical structure and the cyber system. While DAQ system can be supported by various hardware, such as RFID, wireless sensor networks, and 3D laser scanners (Akanmu et al. 2014), the particular DAQ system is selected according to required information type (such as number or image), information accuracy requirement and access to DAQ system hardware.

- Physical-to-Cyber Bridge: information flows from physical components to virtual model through this bridge, which supports the virtual model in real-time tracking of physical structural performance. In addition, the virtual model can also perform real-time structural performance analysis and automate the visualization of structural deficiency at the virtual model.
- Virtual Modeling Platform: The TSM system provides a user interface at the virtual modeling platform, where the end user can monitor the temporary structures remotely and in real-time. Options for the virtual modeling platform for TSM system development included Revit Autodesk, Navisworks Autodesk, and Tekla BIM software. With these virtual modeling platforms listed above, digital information of physical structures can be managed through the 3D virtual models. The exchange of digital information through virtual models is critical as it enables the remote temporary structures monitoring, in addition to visualization.
- Cyber-to-Physical Bridge: The physical structure is monitored by its virtual model through this bridge. For example, the TSM system can instigate corrective action on physical temporary structures by sending instructions to the construction worker through the virtual platform. This information exchange can be achieved through the Cyber-to-Physical bridge.
- Actuators or Portable Devices: The monitoring of temporary structures can be achieved automatically using actuators or through the performance of supervisors. Actuators are usually controlling instruments, which take measures accordingly as required by the system. For example, the ventilation system uses the air damper actuator, which can adjust its position to guarantee the indoor air quality automatically. The corrective action by supervisor for temporary structures monitoring relies on the use of communication tools, such as portable devices, which supports the information exchange between the virtual models and inspector. Through portable devices, the supervisor can receive warning messages and suggestions on temporary structures monitoring.
- On-cloud Database: information exchanged through the CPS bridge is stored in an on-cloud database. The use of the on-cloud database is critical to TSM system for three reasons: (1) structural information of the physical temporary structures can be retrieved frequently by the virtual model, (2) structural performance information is accessible to the portable devices for remote structural monitoring purposes, and (3) history of temporary structures performance is recorded and accessible at the on-cloud database, which enables temporary structural performance enhancement and further analysis in the future. In addition, the use of on-cloud database supports remote access to temporary structural performance

by multiple participants (such as project owner, structural engineer, safety supervisor, and project manager) simultaneously.

- Communication Networks: information exchange between physical structures and their virtual models relies on the communication network. Examples of the communication networks include Local Area Network (LAN), Metropolitan Area Network (MAN), Wide Area Network (WAN), and wireless network (Wi-Fi). Among these communication networks, LAN is usually used at small physical areas, such as offices; the MAN is set up by connecting several LANs into a larger network; WAN usually support the Internet with large distance as it is usually supported by satellite links; finally, as the fastest growing communication network used in daily life, the wireless network provides the physical structures with wireless access to the internet (Studytonight 2014). The selection of communication network depends on the objectives of the temporary structures monitoring.

7.5 TSM Prototype System

The TSM prototype system is developed following a system development framework. This section discusses the framework for TSM system development, along with detailed information on the development of key components (including virtual model, plugin embedded at virtual model, on-cloud database, and mobile APP). After that, TSM system operation is presented with system work and user-interface to demonstrate how TSM works in structural monitoring of scaffold system.

7.5.1 TSM Prototype System Development

According to the TSM system architecture and key system elements discussed above, the TSM system was developed following the system development framework in Fig. 7.3. Each step in the system development framework is discussed in detail in this section.

Key Information TSM relies on key information on a temporary structure's performance (such as inclination and movement) for structural analysis. According to the evaluation of failure mode of scaffold by Yuan (2013), the scaffold structural failure can be categorized into four main cases: base settlement, overloading on the scaffold, insufficient braces of scaffold, and high wind impact. To detect the four common failure cases mentioned above, TSM system requires that the following four structural information should be continuously collected:

1. Loading information on the scaffolding system;
2. Displacement of scaffold planks;

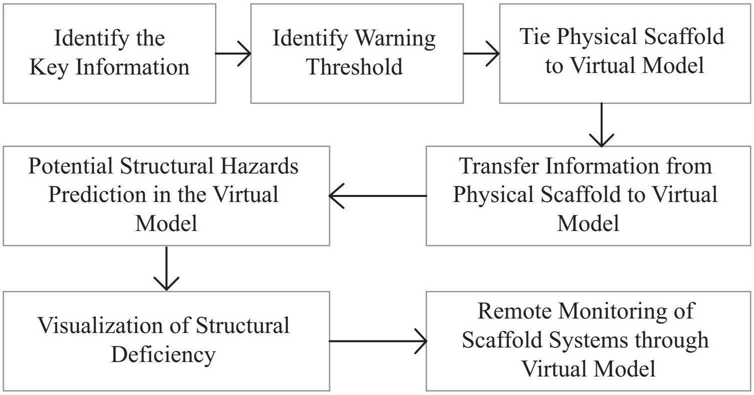


Fig. 7.3 Framework of TSM prototype system

3. Information of connection between the base and scaffold posts;
4. Inclination of the scaffold posts.

With this information collected, TSM is capable of comprehensive structural integrity analysis and structural failure prevention.

Establish Warning Threshold The warning threshold is the reference point used by TSM to determine potential structural failure. Therefore, the TSM system is designed to send warning message automatically when the actual structural information exceeds the selected warning threshold. As temporary structures work in a dynamic environment, the warning threshold has to be appropriately identified so that potential structural failure can be prevented while also allowing the temporary structure to remain functional with reasonable movement.

Although the warning threshold can be set by end users at their preference, the default setting of the TSM warning threshold is determined based on OSHA standards and industrial best practice. For example, the warning threshold of loading on the scaffold system is set according to its working capacity; and the displacement of scaffold planks should not exceed 1/60 of the span; and no disconnection between the scaffold post and ground is allowed.

Tie Physical Scaffold to its Corresponding Virtual Model The physical scaffold is tied to its corresponding virtual model through three main steps:

1. A physical scaffold system should be set up in the physical world (as shown in the right side of Fig. 7.4);
2. Develop a virtual model of scaffolding system in Autodesk Revit. The developed virtual model is then imported into Autodesk Navisworks since Autodesk Navisworks provides open .NET application programming interface;
3. Link physical structure to its corresponding virtual model by registering each physical component with a unique ID in virtual model.

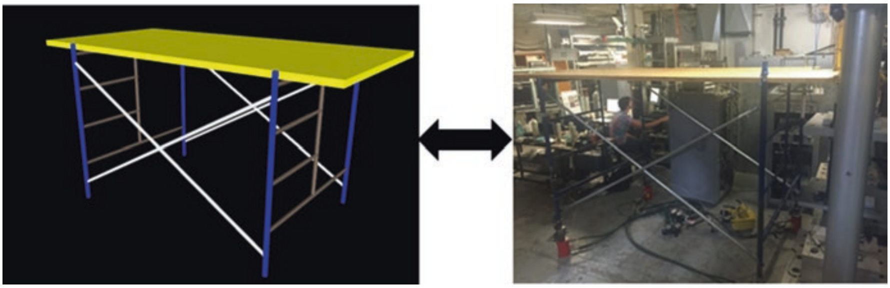


Fig. 7.4 Virtual model and physical set-up of frame scaffold

Transfer Information from Physical Scaffold to Virtual Model Information from the physical component to the virtual world is collected through sensors and transmitted through DAQ system and on-cloud database. In particular, the sensors used by TSM include load cells for loading information, switch sensors for connection information, displacement sensors for displacement of planks, and accelerometer for inclination of scaffold posts. The information on the temporary structure is sent by sensors to NIMAX (National Instrument Measurement & Automation Explorer) for data calibration, and then updated in the on-cloud database.

There are three reasons for the use of on-cloud database for TSM:

1. Information exchange between physical scaffold and its virtual model is supported by the on-cloud database;
2. Multi-user access to the TSM is supported through the on-cloud database;
3. Information exchange between the virtual model and portable devices on the physical components is supported by the on-cloud database.

In particular, the on-cloud database used by TSM is based on the Amazon Elastic Compute Cloud (EC2) as it provides a virtual computing environment, high security, and static IP address for dynamic cloud computing. Both real-time structural information and the records of structural performance of the scaffold system are stored in the on-cloud database.

Potential Structural Hazards Prediction in the Virtual Model The virtual model developed at Autodesk Navisworks supports real-time prediction of potential scaffolding structural failures. In particular, the virtual model is embedded with a plugin, which performs structural analysis based on the information continuously collected from the DAQ system. For example, when the diagonal braces of the scaffold system get disconnected, the disconnected brace will be identified immediately by the plugin.

Visualization of Structural Deficiency To locate the structural problem efficiently, TSM offers visualization of the components in question. Once potential deficiency is detected, TSM will highlight the components in question in an easily identifiable color in the virtual model. The visualization of structural deficiency provides precise information for locating structural problems. This supports safety inspectors and project managers in quick inspection and appropriate monitoring of scaffolding systems.

Remote Monitoring of Scaffold Systems through Virtual Model The remote monitoring of the scaffold system can be obtained through the Cyber-to-Physical bridge. While actuators can be used for automatic correction of potential structural hazards, the sudden movement of the scaffold system caused by actuators may induce instability and imbalance of the workers working on the scaffold structure. Therefore, the remote monitoring is achieved through the automatic warning message and instructions sent by TSM to construction workers. In this case, the information between TSM and construction workers is exchanged through a mobile APP developed at the portable device. It is designed that the mobile APP will be activated and receive a warning message once a potential hazard is identified by TSM. The warning message received at the mobile APP includes an overview of the structural performance, location of the component in question, and description of the identified structural problem. Based on the warning message, the scaffold structure's deficiencies can be corrected by the construction workers.

The APP for TSM is developed on an android platform and continuously checks if there is a warning message from the virtual model every 2 seconds. When a potential structural problem has been identified by TSM, the mobile APP is automatically activated to call the attention of safety inspectors. To ensure that warning message has been received by the end user, the warming alarm will not stop until the end users responds.

7.5.2 TSM Prototype System Operation

To understand how TSM system works for structural monitoring, this section introduces the TSM prototype system operation. In particular, we discuss how the physical scaffold and virtual model are integrated, the work flow of TSM system, and user-interface of TSM for end users.

7.5.2.1 Integration of Physical Scaffold and Virtual Model

Based on the framework of TSM development discussed above, information exchange is the key to the integration between physical structures and their virtual components. To facilitate information exchange, TSM utilizes three main types of services at Amazon EC2:

1. MySQL database. The MySQL on-cloud database provides platform where the most updated structural information is used by TSM for continuous structural

performance analysis; particularly, the information stored at MySQL for TSM includes information on inclination of scaffold posts, loading information on top of scaffold planks, and connection information between scaffold posts and bases.

2. GCM (Google Cloud Messaging) service. The GCM pushes warning notification to portable devices. With the support by GCM, multiple portable devices can receive warning message simultaneously int real-time. With the service by GSM, the portable devices can stay inactive if no warning message is shared which offer economic benefits by saving battery power of portable devices.
3. Linux File System. The Linux file system stores the warning message (in image format) from the virtual model and shares with portable devices upon request. Both the Linux file system and GCM service support the information exchange between the virtual model and portable devices.

Figure 7.5 summarizes the work flow of the integration between the scaffold system and its virtual model. In general, there are 6 main steps for information integration: (1) structural information of scaffold system is updated in MySQL database; (2) Information in MySQL database is continuously used by the virtual model for structural performance monitoring; in case potential structural hazard is identified, (3.1) warning message (image of the virtual model) with component in question highlighted is uploaded to the Linux file system; (3.2) detailed description of identified structural hazards are stored in the MySQL database; (4) description of updated warning message in MySQL database is queried by GCM frequently (every 100 milliseconds); (5) Portable devices receive image of virtual model for warning message and detailed description of warning message from MySQL through GCM service.

7.5.2.2 TSM System Work Flow

To understand how TSM works in the prevention of temporary structures hazards, a workflow of TSM system can be summarized in five steps. A flow chart is also provided in Fig. 7.6.

Details of each step of the TSM system workflow are discussed below:

1. The sensors collect structural information (such as inclination and disconnection information) and send it to DAQ system.
2. The structural information collected from sensors is calibrated by the DAQ system and updated in the on-cloud database.
3. The virtual model continuously collects structural information through the on-cloud database and performs structural performance analysis;
4. Based on the structural performance analysis, a warning message (both image and description of structural performance deficiencies) is sent to portable devices if a potential structural hazard is identified.

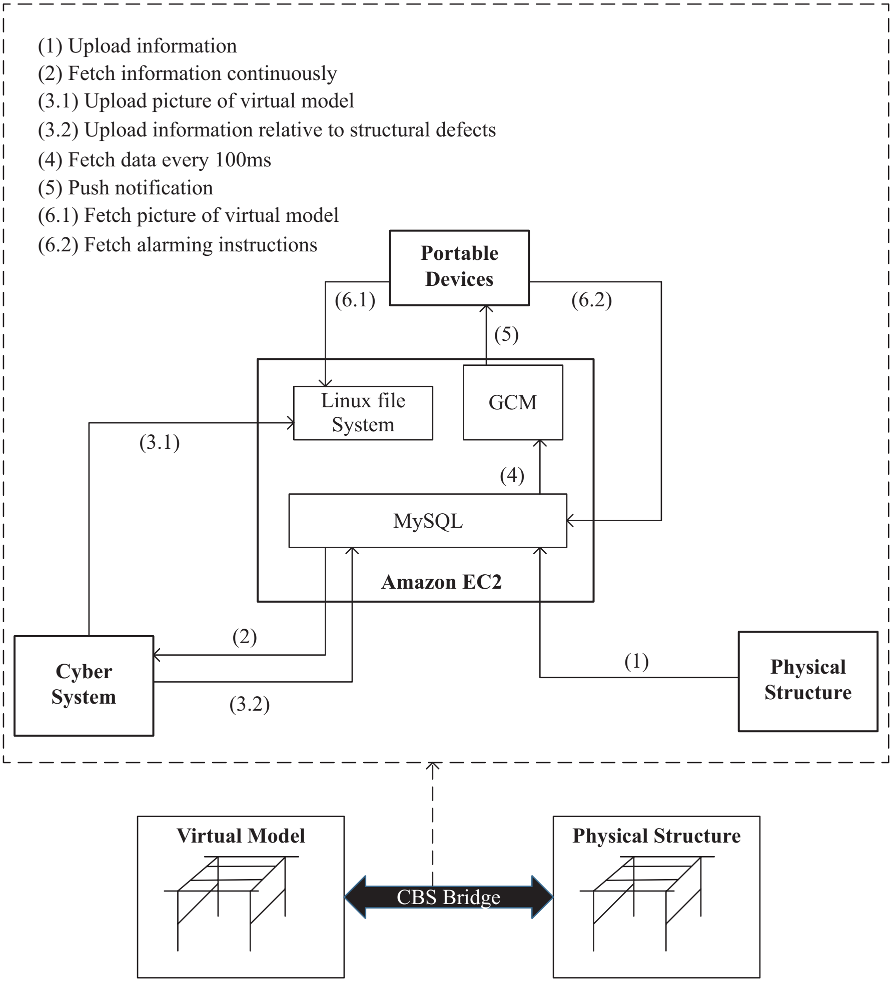


Fig. 7.5 Work flow of integration between physical structural and virtual model

5. Structural deficiency is corrected by the end users (such as safety inspectors, workers, and project managers) based on the warning message. In this way, the potential structural failure is continuously prevented by TSM through real-time monitoring of the scaffold system structure.

7.5.2.3 User-Interface of TSM System

The user-interface of TSM is developed at both the virtual model and the portable devices. The TSM user-interface provides end users access to the TSM system via the virtual model for real-time monitoring of scaffolding system both locally and remotely. The user-interface at the portable device, which provides warning

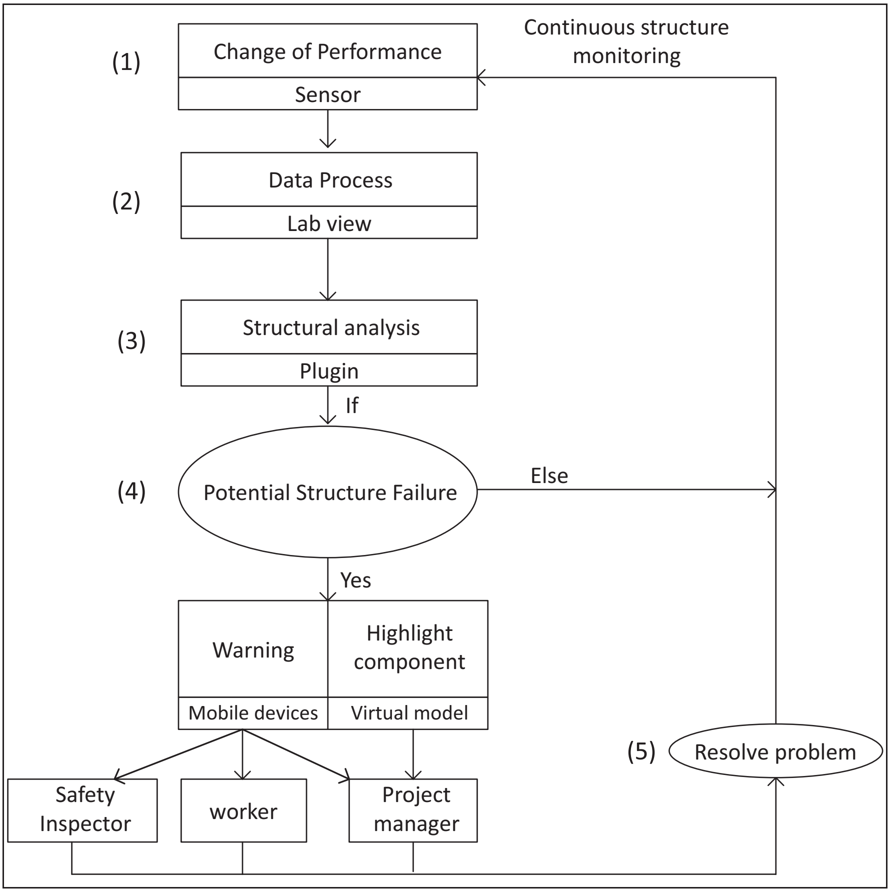
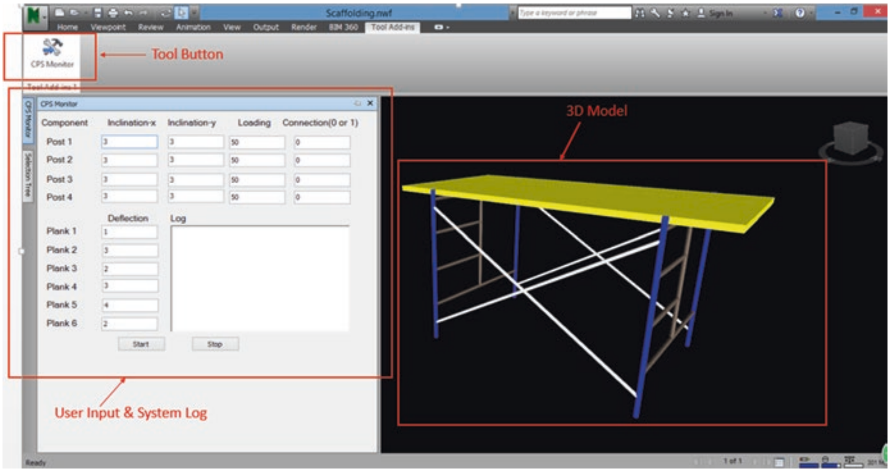


Fig. 7.6 TSM system workflow

information on potential structural hazards to end users, is called the TSM mobile user-interface.

The TSM user interface is shown in Fig. 7.7. Particularly, the end user get access to TSM user interface through the add-in tool in Autodesk Navisworks Management named “CPS Monitor”. The right side of the TSM user-interface displays the scaffold virtual model, which provides a 3D visualization of the scaffold system to the end users. By clicking on the tool button of “CPS Monitor”, a window of user input and system log is displayed, where the threshold value can be reset by end users. With the threshold value satisfied, the end user can run TSM system by clicking the “start” button. While the TSM is running, the structural performance of scaffold system will be checked continuously. If potential hazard is identified, the 3D



Component	Inclination-x	Inclination-y	Loading	Connection(0 or 1)
Post 1	3	3	50	0
Post 2	3	3	50	0
Post 3	3	3	50	0
Post 4	3	3	50	0

	Deflection
Plank 1	1
Plank 2	3
Plank 3	2
Plank 4	3
Plank 5	4
Plank 6	2

Log

Fig. 7.7 User interface of TSM

virtual model shown in the right side of TSM user interface will highlight the components in question to catch attention of users. Meanwhile, TSM user interface will also display how the warning information has been sent to portable devices.

7.6 Experimental Tests and Results

According to Whitaker et al. (2003), base settlement ranks as one of the top causes of scaffolding accidents. To test the performance of TSM under the hazardous status of base settlement, this section demonstrates the experimental test design, test procedures, and test result of TSM under the scenario of base settlement.

7.6.1 Experimental Scenario Design

The experimental scenario of base settlement is simulated as follows: (1) a hydraulic was placed jack at the bottom of each post; the hydraulic provide control of the movement (both upward and downward movement) of each scaffolding post using a manual pump. (2) Lower the hydraulic jack under post 1 up to 3 inches while holding the other posts unmoved. (as shown in Fig. 7.8). This movement simulated the scenario of base settlement under post 1 of the scaffolding system.

Based on the design of experimental scenario discussed above, the hardware used for the experimental test of TSM included:

1. A simple scaffold system;
2. Four Hydraulic Jacks (placed at the bottom of each of the four posts of scaffolding system);

3. One manual pump connected with the four hydraulic Jack to control the movement of each of the hydraulic jack;
4. Four inclination sensors for inclination information of each post;
5. Five switch sensors to check the disconnection information between components of the scaffold;
6. Four load cells to check the loading information at each post;
7. Displacement sensors to check the movement of each post.

7.6.2 Conduct of Experimental Test

As demonstrated in Fig. 7.8, each scaffolding post is placed on top of a hydraulic cylinder. The experimental test of TSM under base settlement scenario is performed as follows: (1) At initial stage, all the four hydraulic cylinders were raised up by 3 inches to keep all the four posts scaffolding system staying at the same level; (2) a bundle of bricks (weighting around 200 pounds) is place at the corner close to post 1. This is to simulate the scenario that a construction worker is working on top of post 1. (3) set the threshold value of base settlement at TSM user interface. The specification of threshold value helps TSM to understand when the warning of potential structural hazards should be raised; (4) with both the physical scaffolding system and structural monitoring threshold set up ready, the TSM monitoring can be started; (5)

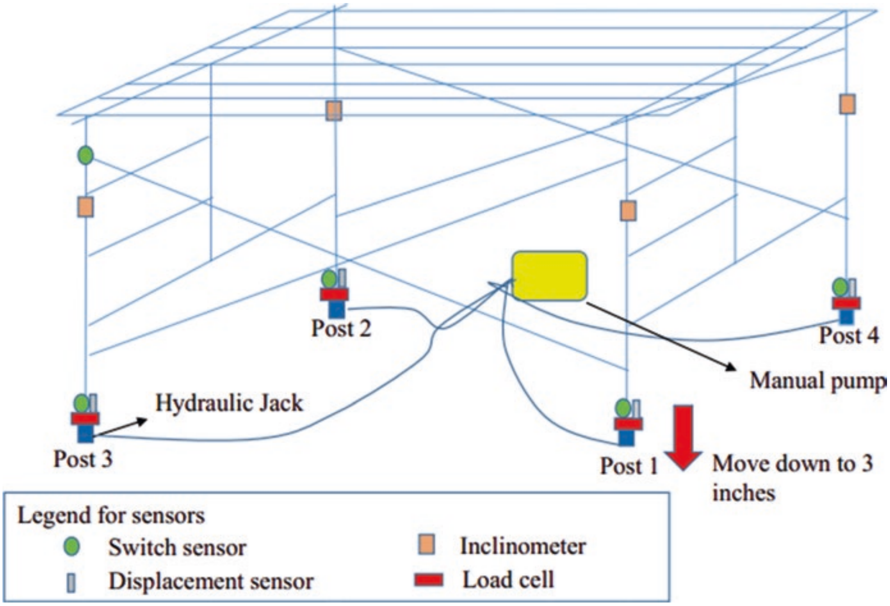


Fig. 7.8 Experimental scenario of base settlement

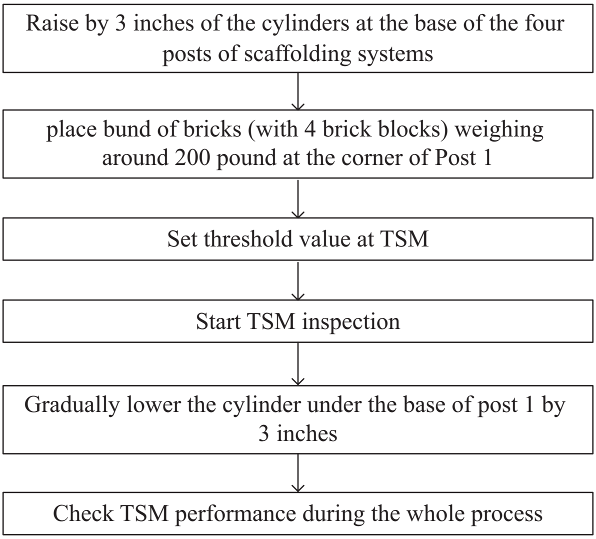


Fig. 7.9 Process of experimental test of TSM

the hydraulic cylinder under post 1 is gradually lowered by 3 inches through the manual pump; (6) information collected by the sensors will be calibrated and uploaded to the database in continuously for structural performance analysis by TSM. Please see Fig. 7.9 for details of the whole experimental test process.

7.6.3 Experimental Test Results

Figure 7.10 show the experimental set up of the TSM test under base settlement scenario. The scaffold shown is set up in the lab; the “virtual model” shown in the lower right side is the virtual model of the scaffold system displayed at the TSM user interface; the “portable device” shown in the upper right side is the devices to be used by the construction workers.

As shown in Fig. 7.11, the experimental test was performed based on the scenario designed and test procedure discussed above. The performance of TSM system is observed during the whole process:

1. At initial stage with no significant base settlement, the “virtual model” shown that everything work fine with no potential structural hazards identified. Similarly, the portable devices stay inactive with no warning message received (refer to Fig. 7.11);
2. Post 1 is lowered gradually through manual pump. It is observed that by the time when the base settlement under post 1 reached 3 inches, potential structural issue has been identified by the “virtual model” with post 2 highlighted in an alarming

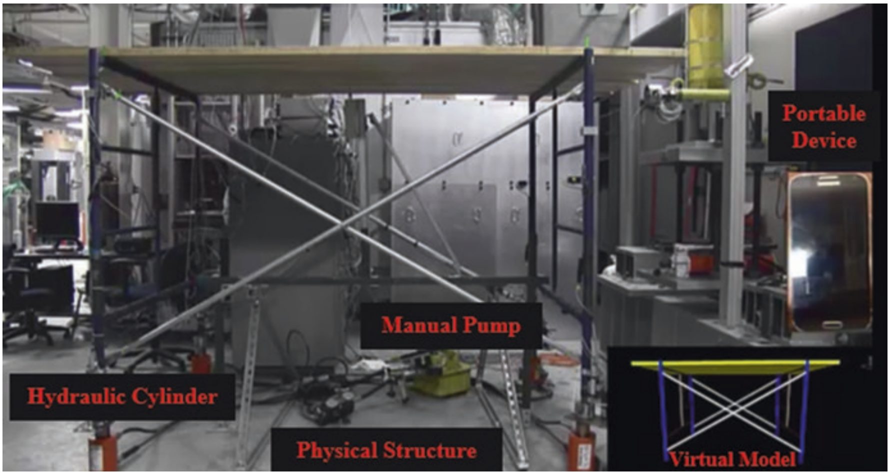


Fig. 7.10 Layout of experimental test

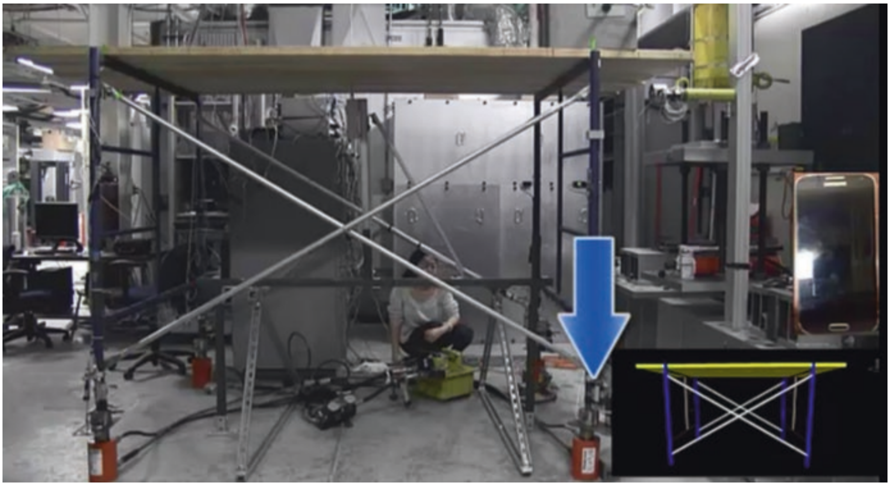


Fig. 7.11 During the process experimental test

color; meanwhile, the portable device also received the warning notification (refer to Fig. 7.12).

3. By tapping the warning notification of the portable devices, the warning message is shown as in Fig. 7.6. Specifically, the warning message displays that the post 2 has potential structural deficiency. This warning message is provided through both image and text format, as shown in Fig. 7.13. To check details of the performance overview, one can click the button of “Details”. According to the performance overview, it clearly pointed that the potential problem of post 2 is due to the disconnection at post 2.

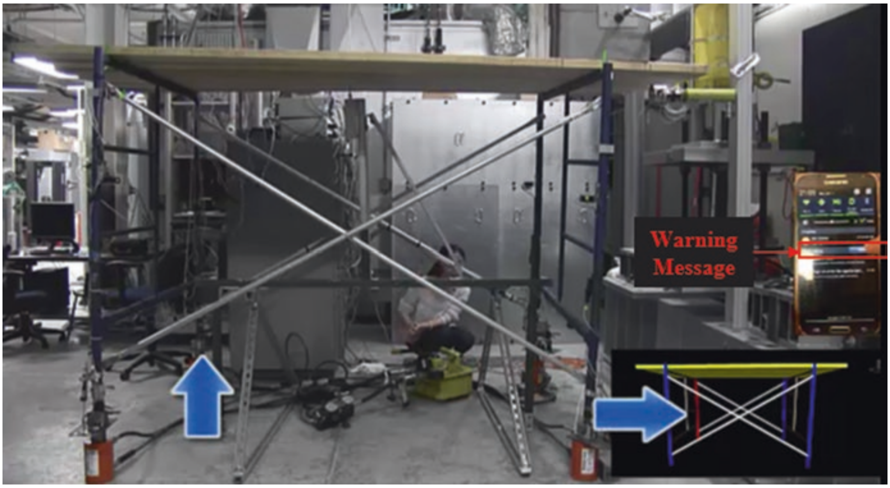
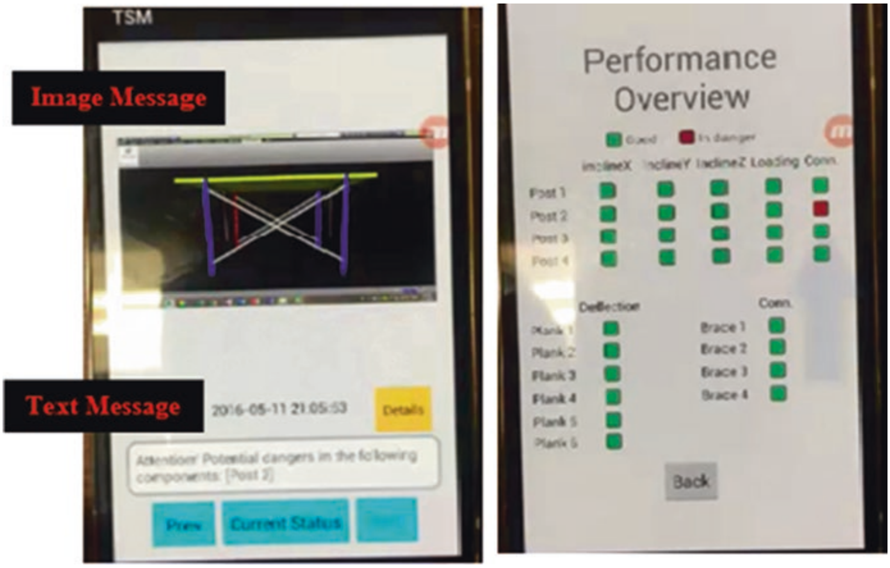


Fig. 7.12 Warning of potential hazard – base settlement



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Attention! Potential dangers in the following components: [Post 2]

Performance Overview

🟩 Good 🟥 In danger

	InclineX	InclineY	InclineZ	Loading	Conn.
Post 1	🟩	🟩	🟩	🟩	🟩
Post 2	🟩	🟩	🟩	🟩	🟥
Post 3	🟩	🟩	🟩	🟩	🟩
Post 4	🟩	🟩	🟩	🟩	🟩

	Deflection
Plank 1	🟩
Plank 2	🟩
Plank 3	🟩
Plank 4	🟩
Plank 5	🟩
Plank 6	🟩

	Conn.
Brace 1	🟩
Brace 2	🟩
Brace 3	🟩
Brace 4	🟩

Fig. 7.13 Warning information of TSM at portable device

According to the test performance of TSM under the experimental scenario, TSM identifies the structural deficiency correctly. In addition, TSM responds to the identified structural problem quickly and provided valuable information to both the safety superintendents and workers.

7.7 Prototype System Evaluation

To obtain an objective and compressive understanding of the TSM system performance, an evaluation of TSM system was performed through an evaluation workshop. This section summarizes of the evaluation participants selection and evaluation outcomes of TSM system.

Evaluation Participants Selection Selection of evaluation participants for TSM system evaluation is based on the targeted beneficiary and users of the TSM system. As the TSM aims to improve management of temporary structures used on the construction jobsite, the use of TSM involves multiple parties. In general, a total of 15 experts with 18 years working experience on average were invited for this evaluation workshop. They are consisted as experts from different areas. For example, three participants were safety superintendents, three participants were safety managers, and nine of the participants are project managers.

Evaluation Outcomes According to the survey feedback and open discussions with the selected experts in construction safety management, TSM system has been valued as very useful in improving the monitoring of scaffolding system for safety management purpose. Details of the evaluation outcomes of TSM system are summarized as follows:

1. Usefulness of TSM system:

14 out of 15 participants have rated the TSM system as extremely useful or very useful in improving the safety monitoring of scaffolding systems (see Fig. 7.14). According to the comments from the participants, the safety of the scaffolding

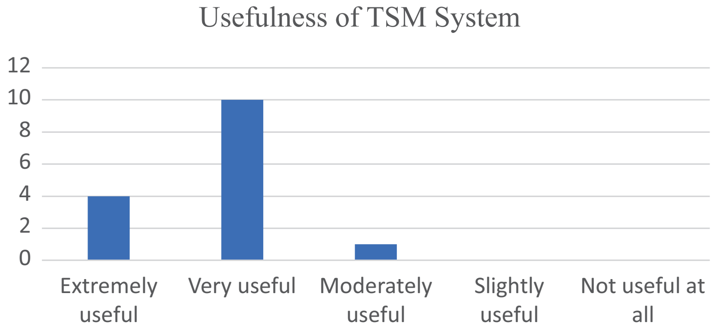

Fig. 7.14 Usefulness of TSM system

system is in high demand of improvement. Currently, there is no similar solution in dealing with the safety issue of scaffolding system as TSM does. They think that the use of TSM increased the opportunity for safety superintendent to monitor high-risk situations; real-time inspection for potential hazards is highlighted as one of the important features that makes the TSM system very useful. In addition to improving safety of scaffolding system, the smooth user interface also improved the usefulness of the TSM system.

2. Accuracy of TSM System:

According to the survey, 14 out of 15 participants think the TSM provides accurate information in identifying potential hazards of scaffolding systems (see Fig. 7.15). The evaluation result indicates that the TSM is capable of providing reliable and accurate warning information for timely prevention of potential failures.

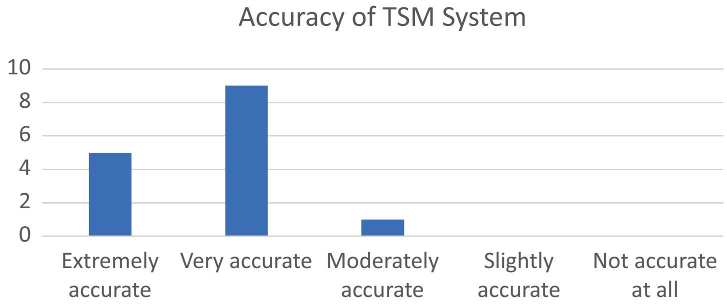

Fig. 7.15 Accuracy of TSM system

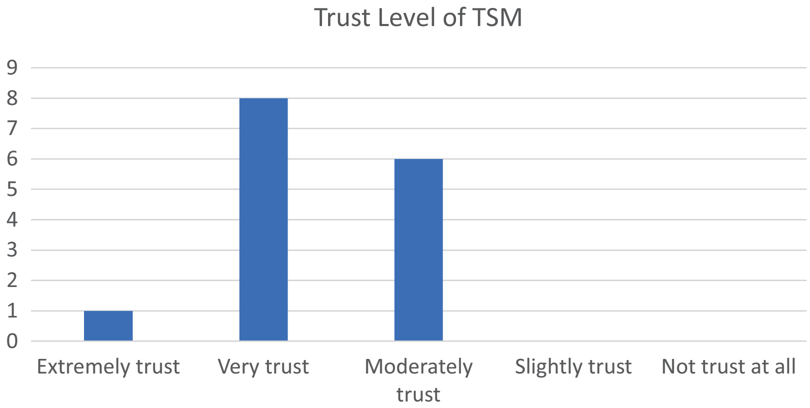

Fig. 7.16 Trust level of TSM by engineering experts

3. Trust level of TSM system

Based on the survey result, TSM is trusted by most of the engineering experts. In particular, 8 out of 15 participants rated the information from TSM system to be "very trust". 6 out of 15 experts trusted the information from TSM "moderately" as they concerned that the TSM needed more additional tests and verification before it can be fully trusted (see Fig. 7.16). Besides, they think the trust level of TSM information also depends on other aspects, including the installation method of TSM hardware, the durability of the monitoring component, the maintenance of TSM, as well as the capability of the person (such as construction workers) who is expected to take actions upon receiving the warning information of TSM.

In summary, TSM system performance has been evaluated by the experts in the area of temporary structures management. According to the feedback from the participants, TSM is very useful in monitoring scaffolding system and provides accurate and can be trusted according to the feedback from most of the participants. TSM has been highlighted by the participants as a potential solution to address the safety issues related to temporary structures.

7.8 Discussions and Conclusions

Safety issues related to temporary structures have drawn increasing attention over the past decades. Continuous structural failures of temporary structures have impacted both the overall safety management of construction project and may cause potential construction delay. While significant amount of efforts has been made by the government and industry for the safe use of temporary structures, there is still urgent need for more safety regulations or advanced methods to address the problem. Among the emerging technologies, CPS has shown advantages in temporary structures monitoring through real-time information exchange between the physical structures and their corresponding virtual models.

Based on the experimental test results and evaluation outcome, we discuss the practical deployment considerations, recommendations for further research as follows. Conclusions of CSP applications to temporary structures are also drawn in this section.

7.8.1 Practical Deployment Considerations

It should be noted that current TSM system collects data from DAQ to the on-cloud database mannually due to system integration limitation. Based on the laboratory test and evaluation workshop, practical deployment considerations for CPS application to temporary structures monitoring in the real world are covered in this section.

Specifically, according to the practical concerns pointed by engineering experts during the evaluation workshop, enhancement is necessary before TSM system can be used in real projects. In general, the CPS approach to temporary structures monitoring can be improved to address the practical concerns with the help of wireless sensors, cameras, laser scanners for quick modeling, and Unmanned Aerial Vehicles (UAVs). Details are described below:

Wireless Sensors One of the limitations of the current CPS approach (TSM system) is the use of wired sensors, which makes the management of cables time-consuming and error-prone. To apply TSM system in the field, wireless sensors would reduce or eliminate the amount of cables to be used while increasing information stability at the same time. Because of these benefits offered by wireless sensors, they have been increasingly adopted for structural health monitoring (Nagayama and Spencer 2007) and personal health monitoring (Milenković et al. 2006).

Use of Cameras Image tracking methods, such as the use of cameras for structural performance monitoring, provide an alternative way of collecting structural information. Technically speaking, the use of cameras can provide accurate information and effectively identify some changes in structural performance. In terms of practical deployment, most construction jobsites are surrounded by cameras for progress monitoring and security. Therefore, it is scalable to take advantage of the existing cameras for temporary structures monitoring.

Laser Scanner for Quick Modeling One of the significant differences between laboratory experiments and field deployment lies in the complexity of temporary structures to be monitored. While it is easy to build a virtual model of a single set of scaffolds for laboratory testing, a quick and clean way of modeling is important in practice. As indicated by the engineering experts during the evaluation workshop and the research literature, laser scanners can measure the distance in millimeter at the speed of hundreds of thousands of points per second (Tang et al. 2010). Because of this, the use of laser scanners provides an accurate and quick method for virtual modeling of temporary structures.

Unmanned Aerial Vehicles (UAVs) UAVs are now increasingly adopted in the construction industry due to its advantage of carrying cameras or laser scanners to capture and generate point cloud models and to automatically detect, classify and localize defects (Skibniewski and Golparvar-Fard 2016). By using UAVs for the TSM system, no cables will be needed for connection between sensors and the DAQ system. This also avoids the effort and costs associated with sensor installation and maintenance, which have been big concerns for practical adoption based on the TSM system evaluation feedback. Furthermore, because of the easy access by UAVs to any dangerous zone at the construction jobsite, it also supports the inspection of the whole temporary structures (including places hard for human access or sensor placement).

All the above methods rely heavily on sensor hardware in collecting structural information on temporary structures. Because of this, the accuracy of structural monitoring highly depends on the appropriate use of sensors, such as the location where the sensor is installed, the type of information that can be collected, or the place where UAVs can fly through and collect information. This dependence on the use of sensors limits the accuracy of the TSM system.

7.8.2 Recommendations for Future Research

While the proposed CPS approach (TSM system) has provided an example of active control of temporary structures through the integration of temporary structures and their virtual components, additional opportunities and benefits can be obtained from CPS for safety management of temporary structures. Possible future trajectories for CPS application to temporary structures monitoring include:

Application of CPS-Based TSM for Practical Site Deployment Although the CPS-based TSM has been developed to enhance the safety monitoring of temporary structures, it has been only tested through laboratory experiments. The TSM system should be enhanced by taking into consideration the practical constraints of a busy construction site. For example, the wired sensors should be replaced by wireless sensors to facilitate installation and maintenance. Meanwhile, the alert mechanism can also be enhanced with a virtual map of the construction jobsite.

Automatic Control of Temporary Structures' Failures Instead of using warning message by the developed TSM system, a more comprehensive application of CPS utilizing actuators can be developed for automatic prevention of structural failures. This is because the actuators can move automatically according to the instructions from TSM.

An Internet of Things (IoT) Approach to Linked Temporary Structures Monitoring Based on the existing CPS-based TSM system, the interdependencies between the components of temporary structures can be analyzed for safety purposes using an IoT approach. IoT enables communication between the individual components of a temporary structure and provides potential benefits such as improved construction coordination, construction site layout monitoring, and structural failures control.

Knowledge-Rich TSM Identifying Causes of Failures During the monitoring of temporary structures, all the information on the temporary structure's performance and system warnings under various conditions are recorded in the database. By taking advantage of binary tree classification model proposed by Liu et al. (2014), the TSM can be more accurate and efficient in offering decision making support to safety superintendents, identifying causes of structural deficiencies, and providing suggestions when similar structural problems occur in the future.

Optimized Emergency Exit Guide in 3D Map The portable devices used by TSM system can be further developed to locate each end user. In this way, the TSM system identifies not only the deficient structural component, but also locates the people working in a dangerous area. With the integration of virtual model of temporary structures and the locations of each end user, the location-based TSM can provide an optimized exit guidance for each end user.

7.9 Conclusions

This chapter explored the application of CPS for enhanced monitoring of temporary structures. Six typical types of temporary structures and the major reasons behind the structural failures were summarized. We further examined the applicability of CPS to temporary structures monitoring by reviewing the existing applications of CPS and enabling technologies for the management of temporary structures. A CPS-based temporary structures monitoring system (TSM) prototype was presented to demonstrate the capacity of the CPS approach to prevent potential failure of temporary structures.

Based on CPS approach, the TSM system enables real-time and remote inspection of temporary structures for potential hazards identification, which would have been difficult visually by a safety superintendent. The experimental testing of TSM demonstrated its efficiency and accuracy under the scenario of base settlement.

Additionally, based on the feedback from the prototype evaluation, the TSM prototype system was deemed to provide for efficient and useful monitoring of temporary structures. In particular, the evaluators highly valued the system in terms of its accuracy, ease of hazard identification, and ease of use. According to the evaluators, the benefits of TSM to temporary structures monitoring include the reduction of injury and death rate; real-time monitoring of the temporary structures; early warnings in identifying potential problems; as well as the prevention of potential hazards which are hard to be diagnosed by human beings.

While TSM has demonstrated the promising approach of CPS to temporary structures monitoring, it is recommended that field tests of the TSM, should be conducted before its adoption in real projects. In particular, the use of cameras for image recognition, wireless sensors, laser scanners, UVA, as well as optical fibers provide complementary methods to support the practical applications of TSM.

In addition to practical deployment exploration of CPS for temporary structural monitoring, research effort can be placed on other potential application areas for further exploration. These potential areas are identified based on the key findings of this project and have been discussed above. In general, they include the use of IOT technology for linked temporary structures monitoring; knowledge-rich temporary structures monitoring system in decision making support; automatic control of temporary structures by TSM, as well as optimized emergency exit guide in 3D map enabled by TSM.

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Chapter 8
Model Checking – Case Study of a Temporary Structures Monitoring System

Dongpeng Xu, Xiao Yuan, Dinghao Wu, and Chimay J. Anumba

8.1 Introduction

Model checking or property checking is a formal computer science method for evaluating the extent to which a model meets a given specification. This involves using appropriate symbolic algorithms to traverse the model and check if the specifications, typically expressed as temporal logic formulas, are met. The effectiveness of cyber-physical systems is dependent largely on how well the cyber and physical elements work together. In such systems, any inconsistencies in the system model could result in either failure or unintended consequences. In this chapter, we present a case study of the model checking of a CPS-based temporary structures monitoring system, which was the presented in detail in Chap. 7. We use model checking to try to detect the vulnerabilities in the system. The case study shows that model checking can identify vulnerabilities in a CPS-based system and help developers fix the vulnerabilities.

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8.2 Temporary Structures Monitoring System

With the objective of real time and remote inspection of temporary structures, Temporary Structures Monitoring (TSM) system has been developed based on the principles of Cyber-Physical System (CPS). The development of the TSM involves the selection of hardware, such as data acquisition (DAQ) instruments, physical temporary structures, and software environments, such as virtual modeling system, DAQ system for data calibration and transmission, database for data storage, and the communication network. These are fully described in Chap. 7 and by Yuan et al. (2016).

8.2.1 System Design

The CPS-based TSM system in our case study consists of physical temporary structures and their virtual models, which are integrated through a CPS bridge. The architecture of TSM system is shown in Fig. 8.1. In general, the physical and cyber system is connected through the CPS bridge, which enables the mutual

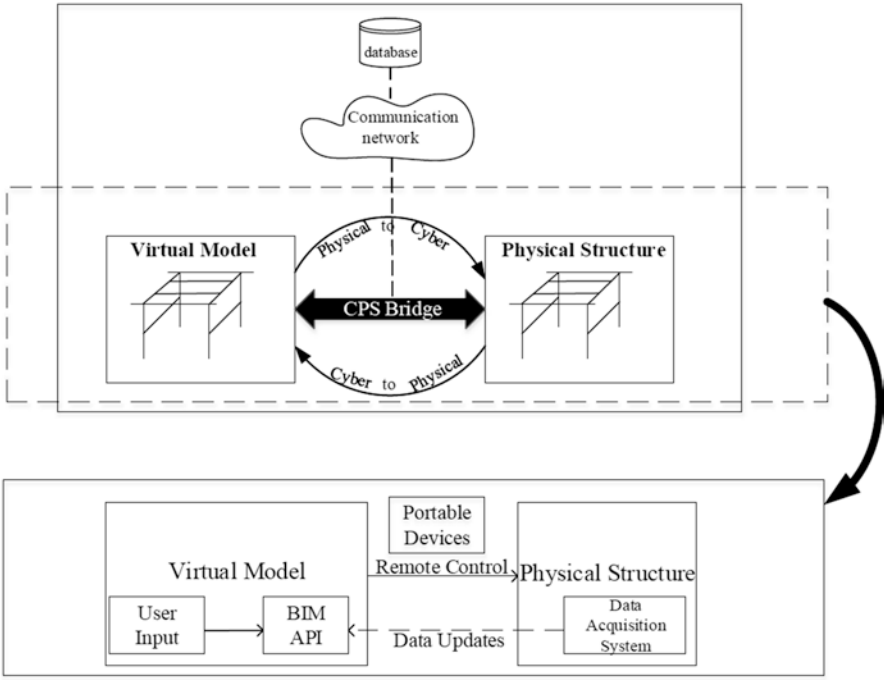


Fig. 8.1 System architecture of CPS-based TSM system

communication between the physical structures and the computing system. In particular, the CPS bridge is supported by the DAQ system and on-cloud database for information collection and exchange; from the physical to cyber system, DAQ system works in transforming information from temporary structures to their virtual model; from the cyber to physical system, the potential hazards of the physical structures will be identified and located in the 3D model, and then communicated to the project managers and safety supervisors through portable devices to take actions to prevent potential accidents.

Generally the prototyping system works in the way that first of all the DAQ system attached to the temporary structures continuously collect and sends information to the database; second, the CPS-based TSM system conducts structural performance analysis every 2 seconds; third, if potential structural failure has been identified, the 3D model will highlight the corresponding components in alarming color. To guarantee timely communication of the potential hazards, the warning message will also be sent to the construction workers and other safety supervisors through portable devices for immediate attentions. Based on the warning information of potential location and causes of problems, the construction workers and project managers shall take corresponding actions to prevent temporary structures accidents. The system workflow is displayed in Fig. 8.2.

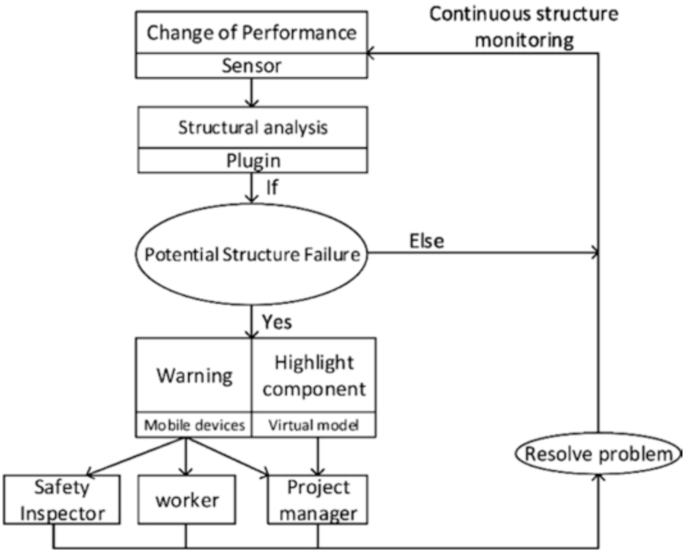
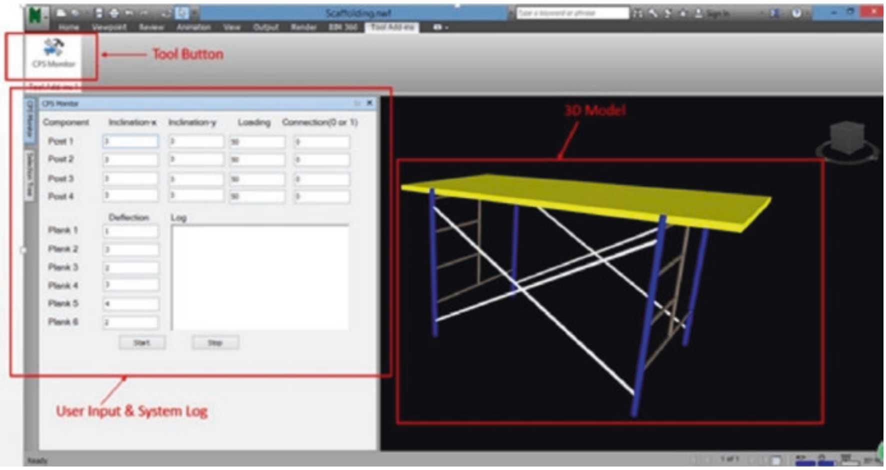


Fig. 8.2 System workflow

8.2.2 System Operation of CPS-Based Temporary Structural Monitoring

As shown in Fig. 8.3, the TSM system prototype enables the interaction between temporary structures and computing system through a virtual model platform, which is developed as a plug-in at Autodesk Navisworks. This plug-in is named as "CPS Monitor". The user-interface of the TSM system consists of the 3D model of temporary structures and the table of property of each component. By clicking the tool button of "CPS Monitor", the window of TSM system appears with the value of warning threshold and system log window presented. The threshold value for each component is identified based on several criteria, including official regulation, practical concerns as well as the capability of the materials used. In particular, the threshold value of the inclination of each component is set according to the requirement of safety managers based on their project experience. The loading threshold is identified based on the component capability specified by the manufacturers' guide while the threshold value of base settlement is based on practical concerns, as the disconnection is an obvious signal indicating the base settlement. The threshold value for plank displacement is set according to the OSHA regulation. For user-friendly consideration, the threshold value is updated and saved based on the last record. Users can modify the threshold value frequently at their convenience. By clicking the "start" button, the TSM system evaluation of temporary structures starts. In general, the information is updated every 2 seconds continuously to check the change of temporary structural integrity. Base on the evaluation result, the TSM system responds correspondingly if potential hazards have been identified. At the virtual model, the components in question will be highlighted with alarming color for immediate attention. To make sure all the workers have received the warning



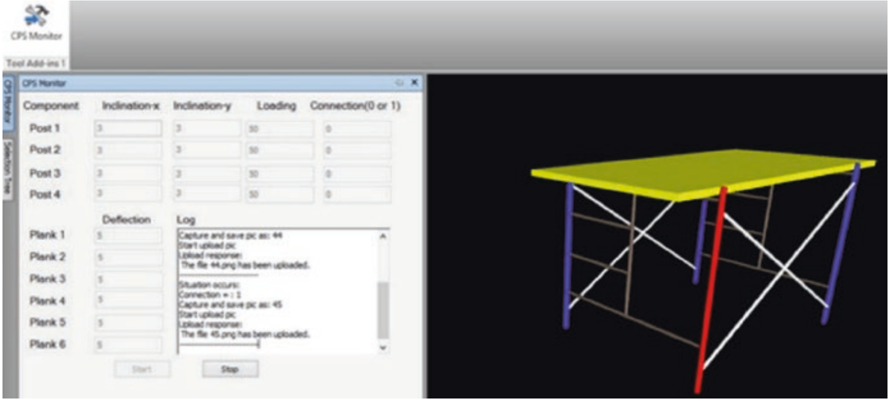
CPS Monitor

Component	Inclination-x	Inclination-y	Loading	Connection(0 or 1)
Post 1	3	3	50	0
Post 2	3	3	50	0
Post 3	3	3	50	0
Post 4	3	3	50	0

	Deflection
Plank 1	1
Plank 2	3
Plank 3	2
Plank 4	3
Plank 5	4
Plank 6	2

Log

Fig. 8.3 User interface of CPS-based TSM system



Component	Inclination-x	Inclination-y	Loading	Connection(0 or 1)
Post 1	3	3	50	0
Post 2	3	3	50	0
Post 3	3	3	50	0
Post 4	3	3	50	0

	Deflection
Plank 1	5
Plank 2	5
Plank 3	5
Plank 4	5
Plank 5	5
Plank 6	5

Log

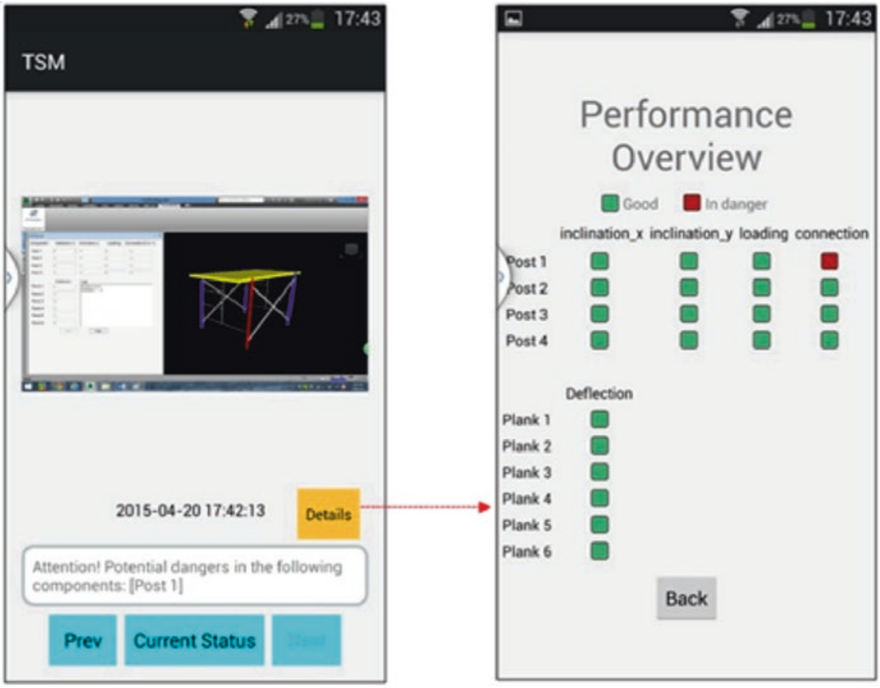
```
Capture and save pic as: 44
Start upload pic
Upload response:
 The file 44.png has been uploaded.
-----------
Situation occurs:
Connection = : 1
Capture and save pic as: 45
Start upload pic
Upload response:
 The file 45.png has been uploaded.
-----------
```

Fig. 8.4 Warning instructions at the 3D virtual model

message, the log window close to the virtual model demonstrates the working progress of the system indicating if the warning messages have been sent to the workers on the construction job site (as shown in Fig. 8.4). Take the base settlement of a frame scaffold for example; one can easily noticed that there is a potential problem due to the structural deficiency of one scaffold post (highlighted in red). Meanwhile, for the end users carrying portable devices, alarms along with detailed information of the structure deficiencies will be displayed through the mobile app of "TSM" installed in the portable devices. For a quick view of the potential problem, a picture of the 3D model with highlighted components in alarming color will be presented with a few text message stating the components in problem (as shown in Fig. 8.4). If the end user wishes to have detailed information, he or she can tap the button of "detail", which then displays the analysis of structure performance of each component (as shown in Fig. 8.5). In this case, the construction workers can immediately understand that the structure deficiency of the post is due to the ground settlement of post 1. With this information, the end users are expected to have a better understanding of the hazardous situation and take corrective actions to address potential structural failures and injuries.

8.3 Model Checking CPS

Model checking methods are useful for systems that have complicated transition relations. The design of CPS is one of these situations. There are some existing work on CPS verification using model checking related techniques. Akella and McMillin (2009) encode the physical system properties into a discrete event system and the CPS is described using the Security Process Algebra. Then the authors apply a model checking called CoPS to check the system's security against all high level potential interactions. At last, they verify a model problem of invariant



2015-04-20 17:42:13

Attention! Potential dangers in the following components: [Post 1]

Performance Overview

🟩 Good 🟥 In danger

	inclination_x	inclination_y	loading	connection
Post 1	🟩	🟩	🟩	🟥
Post 2	🟩	🟩	🟩	🟩
Post 3	🟩	🟩	🟩	🟩
Post 4	🟩	🟩	🟩	🟩

	Deflection
Plank 1	🟩
Plank 2	🟩
Plank 3	🟩
Plank 4	🟩
Plank 5	🟩
Plank 6	🟩

Fig. 8.5 Warning instructions at the portable devices

pipeline flow. In this paper, we use temporal logic model checking to verify and improve a CPS model. Compared to their method, our work is more general to check more potential bugs in a cyber-physical system.

Clarke and Zuliani (2011) apply statistical model checking to CPS verification. Statistical model checking combine the Monte Carlo method with temporal logic model checking. It samples the behaviors of the system model, check their consistency with the temporal logic formula, and finally calculate an approximate value for the probability that the formula is satisfied. The authors successfully verified a fuel control system for a gasoline engine as a CPS example. Different from this work, we use conventional model checking rather than statistical model checking, so our method verifies all system behaviors.

Bu et al. (2011) propose that instead of offline modeling and verification, many CPS should be modeled and verified online. The authors focus on the system's time bounded behavior in short-run future, which is more describable and predictable. They study two cases of their ongoing projects, one on the modeling and verification of a train control system, and the other on a Medical Device Plug-and-Play (MDPnP) application to show that fast online modeling and verification is possible. Compared to their method, our research has different application focus. The CPS in our research does not develop fast. Moreover, we introduce model checking during the process of CPS design and improve the design in several iterations.

There are also other research work (Derler et al. 2012; Karsai and Sztipanovits 2008; Bhave et al. 2011; Banerjee et al. 2012) involving modeling cyber-physical systems. These works mentioned the possibility of applying model checking to verifying CPS, but did not propose a detailed method. In our research, we describe a concrete method to build and verify a CPS model, and provide a case study to show the model checking procedure in a temporary structures monitoring system.

8.4 Spin: The Model Checker

Model checking is a formal method for automatically verifying whether a system meets a set of properties. Model checking tools, such as SMV (Clarke 2009), NuSMV (Cimatti et al. 2000), Spin (Holzmann 1980), and Java Pathfinder (Visser et al. 2003), have been widely applied in verification of hardware and software systems.

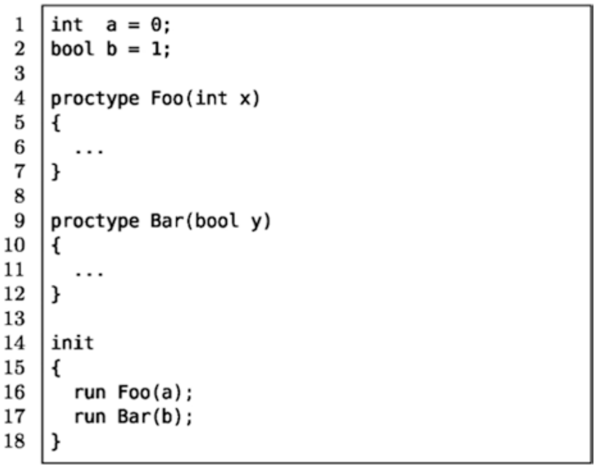
Spin (Holzmann 1980) is a widely used model checker. It was originally designed for verifying communication protocols and gradually grows into a powerful verification tool. It is often used to check concurrent systems such as multi-thread software or distributed systems.

Spin is often applied to verify the logic consistency of concurrent systems, which is described using Promela (Holzmann 2004), the specification language for Spin. People use Promela to model the communication between different processes. For ease of understanding the TSM system model written in Spin, we briefly introduce the core part of the Promela language and how to write the specification in Spin. We only present the essential components that is related to the model in this chapter. More details are included in reference books such as Holzmann (2004). In addition, there are many textbooks about verification of systems by formal methods checking (Huth and Ryan 2004; Manna and Pnueli 2012a; Manna and Pnueli 2012b; Roscoe 1997; Holzmann 2007). A Promela model usually includes the following parts:

1. Variable declarations
2. Process declarations
3. Initial process

Figure 8.6 shows an overview of a typical Promela program. Line 1 and 2 declare variables a and b and initialize them. a is an integer variable which is initialized to 0. Similarly, b is a Boolean variable that is initialized to one. Line 4–12 declares two process called Foo and Bar. In Spin, a process is a function that can execute concurrently with all other processes. Line 14–17 define the initial process for launching processes. We will explain more details about the Promela language in Sect. 8.4 when describing the model of the temporary structural monitoring system.

As mentioned before, model checking method is to automatically verify whether $\mathcal{M}, s \vdash \phi$ holds, in which $\mathcal{M}$ refers to the model described using Promela. We also need to use a formal notation to present the properties ϕ. As a practical model checker, Spin provides several properties that can be checked, such as assertions,



```
int  a = 0;
bool b = 1;

proctype Foo(int x)
{
  ...
}

proctype Bar(bool y)
{
  ...
}

init
{
  run Foo(a);
  run Bar(b);
}
```

Fig. 8.6 Promela program overview

deadlock, linear temporal logic (LTL) formulas and unreachable code. In this chapter, we only use assertions and LTL formulas to specify the properties. The syntax of assertion statement is assert (<expr>). If the expression expr is evaluated to a non-zero value, the assertion statement is passed; otherwise, Spin will terminate and report an error. Moreover, Spin has its own syntax for LTL formulas as follows:

1. [] P: Always P, which corresponds to the G ϕ predicate in LTL.
2. <> P: Eventually P, which corresponds to the F ϕ in LTL.
3. P U Q: P is true until Q becomes true, which corresponds to the ϕ_1 U ϕ_2 predicate in LTL.

8.5 Modeling the Temporary Structures Monitoring System

This section presents the model checking process and result. We use the Spin model checker (version 6.4.3) released in December 2014. In our implementation, each time when Spin report one property does not hold, the checking process stops and will not continue checking the following properties. It is because that usually one bug leads to multiple violations of the properties. The violation report for one property is enough for the designers to fix the problem. Moreover, reporting one violation each time helps designers focus on one bug each time to save their effort and time.

In this case study, we apply the model checking technique as follows. First, the designers provide us with the initial version of the system design, which is called “Design A.” Then we encode it as a Spin model, which is called “Model A”. We also implement the properties in Spin. After that, we run the Spin model checker to check Model A. The checking result shows whether each property passes or not. For the failed test, Spin provides a counterexample and the related backtrack information. We return the checking result to the designers and they confirm whether the counterexample is a real bug. If it is confirmed, the designers will fix them and update the system design to “Design B.” After that, we also update the model to “Model B” accordingly. Note that the properties remain the same during the whole model checking procedure. Therefore, we ran Spin again to check the Model B. The checking and revising procedure was repeated until the model passed the model checking for all properties.

Table 8.1 shows the model checking result. The first column presents the models that are built based on different versions of the CPS-based TSM system design. The second to the fourth columns shows the model checking result on different properties. “X” means the corresponding property holds in that model and “$\surd$” means it does not hold. “-” represents that the property is not verified in that model. We reported the violated properties to the designers and they confirmed that they are real bugs in the corresponding design. The following sections provide the details of our discovery and the fix approach in each design and model.

8.5.1 Overview

This section presents the model to describe the cyber-physical system. As shown in Fig. 8.4, the TSM system is a scaffold monitoring system. The left part is a panel that receives the user’s input to configure the threshold for the inclination, loading and so on. The log frame displays the checking ongoing status. Besides, there are “start” and “stop” buttons at the bottom. Users can click them to start or stop the checking procedure. The right part in Fig. 8.4 shows a simulation picture of the scaffold. The TSM system will highlight the component in red color when it is likely to be dangerous; otherwise, it will show the safe component in blue. The TSM system includes sensors placed on the scaffold, which are able to monitor the bending, loading, and other features of a component. The checking procedure periodically fetches data from sensors and then analyzes the data to see whether they exceed the configured threshold.

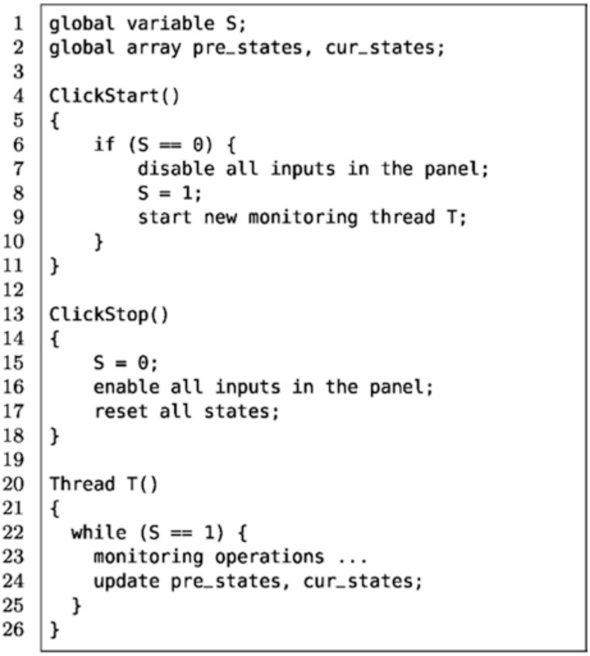
Table 8.1 Model checking result

Model	Property			
	1	2	3	4
A	✓	×	-	-
B	✓	✓	×	-
C	✓	✓	✓	×
D	✓	✓	✓	✓

8.5.2 Design A

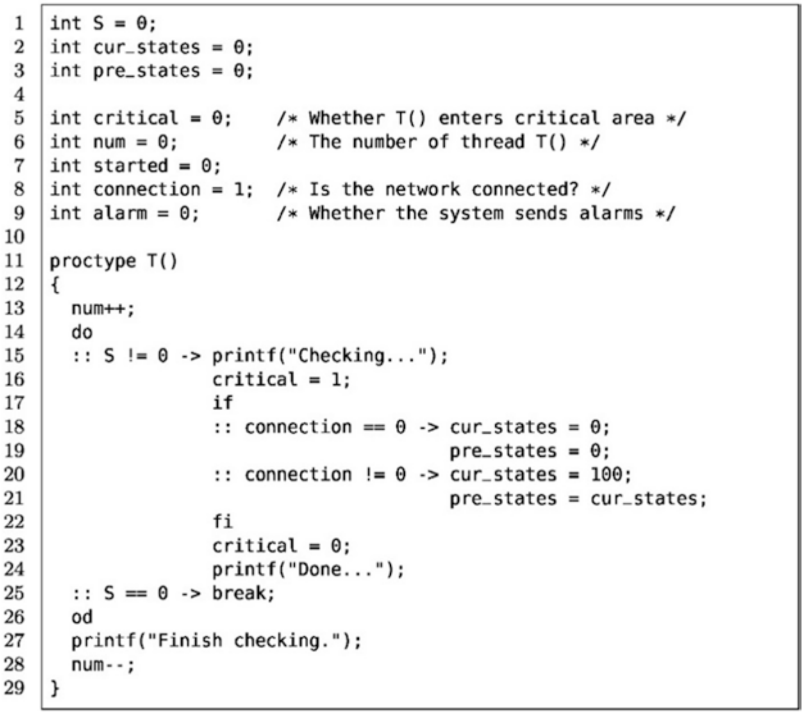
In this section, we describe the initial design of the TSM system, which is called “Design 1” in this case study. This is the first version the system designers gave to us. The pseudo code in Fig. 8.7 shows “Design A”. In this chapter, we use pseudo code (Fig. 8.7) to present the design and use Spin code to show the model in Spin (Fig. 8.8). In Fig. 8.7, the function ClickStart is triggered when users click the start button. Similarly, ClickStop is triggered when clicking the stop button. Thread T() implements the monitoring functions in a while loop. The thread test the global variable S before each round of monitoring. It ends monitoring when S equals zero. Therefore, ClickStart and ClickStop set S to start or stop the monitoring thread T().

As shown in Fig. 8.7, there are two global array variables: pre_states and cur_states. cur_states stores the current risk states of each component and pre_states stores the risk states in the last round of monitoring. They are used to implement the monitor function in line 23 and 24 in Fig. 8.7. Here we briefly describe how it works. First, the monitoring thread T() fetch data from the sensors and store them in a system buffer. Then T() check each component’s data with the threshold and update the array cur_states accordingly. The monitoring thread sends an alarm when the cur_states of one component is true and the pre_states is false, which means the risk is happening. At the end of each round of monitoring, all states in cur_states are copied to pre_states.



```
 1  global variable S;
 2  global array pre_states, cur_states;
 3
 4  ClickStart()
 5  {
 6      if (S == 0) {
 7          disable all inputs in the panel;
 8          S = 1;
 9          start new monitoring thread T;
10      }
11  }
12
13  ClickStop()
14  {
15      S = 0;
16      enable all inputs in the panel;
17      reset all states;
18  }
19
20  Thread T()
21  {
22    while (S == 1) {
23      monitoring operations ...
24      update pre_states, cur_states;
25    }
26  }
```

Fig. 8.7 The initial design of the TSMS



```
 1  int S = 0;
 2  int cur_states = 0;
 3  int pre_states = 0;
 4
 5  int critical = 0;    /* Whether T() enters critical area */
 6  int num = 0;         /* The number of thread T() */
 7  int started = 0;
 8  int connection = 1;  /* Is the network connected? */
 9  int alarm = 0;       /* Whether the system sends alarms */
10
11  proctype T()
12  {
13    num++;
14    do
15    :: S != 0 -> printf("Checking...");
16                 critical = 1;
17                 if
18                 :: connection == 0 -> cur_states = 0;
19                                       pre_states = 0;
20                 :: connection != 0 -> cur_states = 100;
21                                       pre_states = cur_states;
22                 fi
23                 critical = 0;
24                 printf("Done...");
25    :: S == 0 -> break;
26    od
27    printf("Finish checking.");
28    num--;
29  }
```

Fig. 8.8 Global variables and T() in Model A

We build a model checker in Spin to simulate "Design A." The Promela model is shown in Figs. 8.8 and 8.11, which is called "Model A." Figure 8.8 presents how the global variables and the monitor process T() is modeled in Spin. Figure 8.11 shows the model of the function ClickStart and ClickStop. The code is clearly aligned and the variables' name are consistent with those in "Design A." However, the syntax of Promela might lead to some trouble to understand the code. We briefly explain the code as follows.

In Fig. 8.8, line 1 to line 9 define several global variables. The syntax of variable declaration in Promela is the same as that in the C programming language. Variables can be initialized with an initial value when being declared. Basic type variables are initialized with 0 as the default initial value. Promela supports plenty of types such as byte, integer, Boolean, array, record and so on. We only introduce those types that appear in this chapter. The language menu provides a full description of the types in Promela. Line 1–3 in Fig. 8.8 define the corresponding global variables in the TSMS. Line 5–9 defines several global variables for checking different properties. For instance, critical indicates that the monitoring thread enters an area that could cause race condition problem. It is because T() and ClickStop both have the capability to modify the content in pre_states and cur_states. num refers to the number of thread T() at the same time. Connection simulate the network connection. Alarm means whether the system sends an alarm.

Lines 11–29 define the monitoring process T(). A process is a function that can execute concurrently with all other processes. Since Spin is originally designed to check communication protocols, which usually involve sending and receiving messages between two independent machines, the process concept naturally simulates the communicating subjects. A process is defined by the proctype keyword. Each process can have its own local variables and execution status.

The do loop from line 14–26 in Fig. 8.8 simulates the monitoring procedure. do statement is the loop statement in Promela. Inside the loop, line 17–22 use a branch statement to handle the different situations when the network is connected or not. The branch statement and loop in Spin have a similar form, which is shown in Figs. 8.9 and 8.10. For the branch statement, there are n branches in one if statement. Each branch includes a guide cond_n and the following statements stmt_n_1; stmt_n_2; … . If at least one guide is evaluated to a non-zero value, Spin will nondeterministically choose one branch to execute. The else branch will be executed if all other guards are zero. Moreover, as shown in Fig. 8.10, the loop statement in Promela looks similar to the branch statement, except replacing the keyword if with do. The difference between do statement and if is that, do statement continues the next round of execution after running one branch. A break statement can exit a do loop and transfers the control flow to the end of the loop.

In the do loop in Fig. 8.8, we ignore the trivial details such as fetching data from sensors since they are not the key parts for model checking. We only use two assignments to abstract the procedure of updating pre_states and cur_states. The variable started is used to synchronize ClickStart and ClickStop, because in the TSM system design, users are not able to click the start button or modify any inputs in the panel when T() is already running. Therefore, started is used to simulate the operation to enable or disable all inputs in the panel.

Figure 8.11 shows the remaining part of Model A. ClickStart sets S to 1 and then run the monitoring thread T() and ClickStop set S to 0 and flush pre_states and

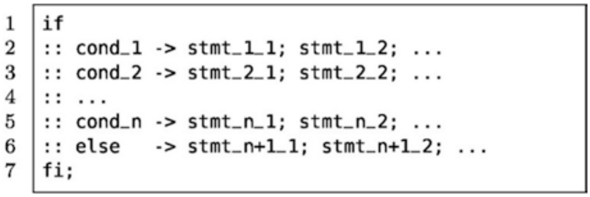


Fig. 8.9 If statement in Promela

```
if
:: cond_1 -> stmt_1_1; stmt_1_2; ...
:: cond_2 -> stmt_2_1; stmt_2_2; ...
:: ...
:: cond_n -> stmt_n_1; stmt_n_2; ...
:: else   -> stmt_n+1_1; stmt_n+1_2; ...
fi;
```

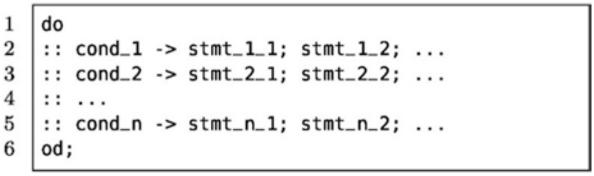


Fig. 8.10 Do statement in Promela

```
do
:: cond_1 -> stmt_1_1; stmt_1_2; ...
:: cond_2 -> stmt_2_1; stmt_2_2; ...
:: ...
:: cond_n -> stmt_n_1; stmt_n_2; ...
od;
```

```
proctype ClickStart()
{
  do
  :: atomic {started == 1 -> skip;}
  :: atomic {started != 1 -> started = 1; break;}
  od

  if
  :: (S == 0) -> S = 1; run T();
  fi
}

proctype ClickStop()
{
  do
  :: started == 0 -> skip;
  :: started != 0 -> break;
  od
  S = 0;
  printf("Stop.");

  critical++;
  cur_states = 0;
  pre_states = 0;
  critical--;
  started = 0;
}
```

Fig. 8.11 ClickStart and ClickStop in Model A

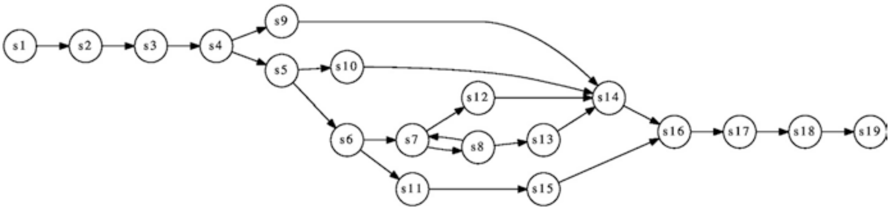


Fig. 8.12 The state transition diagram of Model A

cur_states. Moreover, since flushing pre_states and cur_states in ClickStop could cause race conditions with other threads, we also put critical update operations around for future checking.

Figure 8.12 shows the state transition diagram of Model A. The diagram shows that even a relatively simple model can have many states with complicated relation between them. It is very difficult for human to enumerate and track each path in the state transition system. Therefore, automated model checking approach is helpful to solve this problem. In this state transition diagram, each state contains every variable and its value. Due to the page limitation, we only show several example states here rather than the description of every state. For instance, s1 is the initial state. All variables in s1 is 0 except connection. For simplicity, we ignore those variables whose value equals to zero. Thus s1 can be represented as {connection = 1}. Similarly, s2 is {connection = 1, started = 1}.

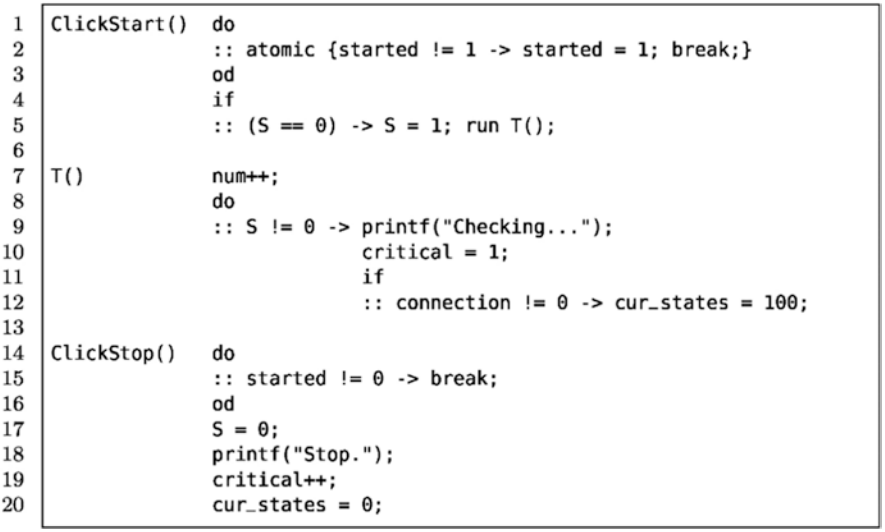
8.5.3 Properties

So far, we have introduced the initial design and model we used to describe the TSM system. In this section, we present the specifications used to check the model. The TSM system is a multi-process system, so common problems such as race condition need to be checked. Moreover, we discuss with the TSM system designers to select a set of properties based on the following two criteria. First, they are true properties, which means they should hold during the execution of the TSM system. Second, they are security related. Violation of these properties will cause severe bugs happen. Generally, we check the properties as follows:

1. `(critical==0 && started==0 && S==0) U (S==1)`: The TSMS is stopped initially until it is started at the first time. This property is used to check whether the initial values are set correctly. S = 0 means the monitoring thread is not stated. Therefore, this property ensures that the global variables critical and started are initialized correctly.
2. `[] (critical! = 2)`: Critical region is the part of a thread that involves update a global variable shared with other threads. Obviously, only one thread can run its critical region at the same time. The variable critical is increased when entering the critical region and decreased when exiting. Thus critical should never equal to 2 during the run time of the system.
3. `[] (thread_num < = 1)`: By the design of the TSMS, only one monitoring thread T() executes at the same time. Since there is no lock for the global variables such as cur_states and pre_states, running T simultaneously could cause race condition. The variable thread_num counts the number of T() running at the same time, so it should not be greater than 1.
4. `[] (connection==0 - > alarm==1)`: This property checks that the TSMS should send an alarm, when the network is disconnected. Connection equals 0 when the network is disconnected and alarm equals 1 when the system is sending an alarm.

8.5.4 Check Design A

As shown in Table 8.1, Model A passes in the model checking of property 1 however fails in that of property 2. Property 1 means that the global variables are correctly initialized. The violation of property 2 indicates that there are multiple threads entering the critical region at the same time. Spin is able to print the counterexample

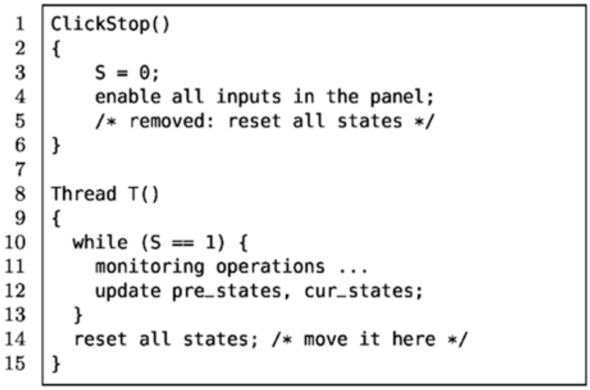


```
 1  ClickStart()  do
 2                :: atomic {started != 1 -> started = 1; break;}
 3                od
 4                if
 5                :: (S == 0) -> S = 1; run T();
 6
 7  T()           num++;
 8                do
 9                :: S != 0 -> printf("Checking...");
10                             critical = 1;
11                             if
12                             :: connection != 0 -> cur_states = 100;
13
14  ClickStop()   do
15                :: started != 0 -> break;
16                od
17                S = 0;
18                printf("Stop.");
19                critical++;
20                cur_states = 0;
```

Fig. 8.13 The path to produce the counterexample in Model A

for the violated property. Furthermore, Spin can show the state transition path on how to reach the counterexample. Figure 8.13 shows one path to reach the race condition that violates property 2. First, thread ClickStart is executed until line 9 in Fig. 8.11 then invoke the monitoring thread T(). Next, T() is executed to line 21 in Fig. 8.8. Finally, ClickStop is invoked and runs until line 23 in Fig. 8.11. Obviously, the thread T() and ClickStop both reach the critical region to modify the content of cur_states, which will cause the race condition. At the line 20 in Fig. 8.13, the variable critical equals to 2. Therefore, this counterexample triggers the violation of property 1: [] (critical! = 2).

We reported the counterexample and the path to the TSM system designers and they confirmed that this is a real bug in the system design. This bug means clicking stop button could lead to flushing the pre_states and cur_states when checking the status of the scaffold, and thus the TSM system could miss some risky situations. In order to fix this bug, the designers moved the flushing operation from ClickStop to the end of T(). Therefore, only T() is able to update the pre_states and cur_states and the race condition is eliminated. Figure 8.14 shows the updated design, which is called “Design B” in our case study. Due to space limitations, when presenting the updated design in each round of model checking, we only show the parts that are different from the previous design and the comments in the code indicate the modification. For instance, as shown in Fig. 8.14, the designers only updated the function ClickStop and T(). We follow this style to present each updated design in the rest of this chapter.



```
ClickStop()
{
    S = 0;
    enable all inputs in the panel;
    /* removed: reset all states */
}

Thread T()
{
  while (S == 1) {
    monitoring operations ...
    update pre_states, cur_states;
  }
  reset all states; /* move it here */
}
```

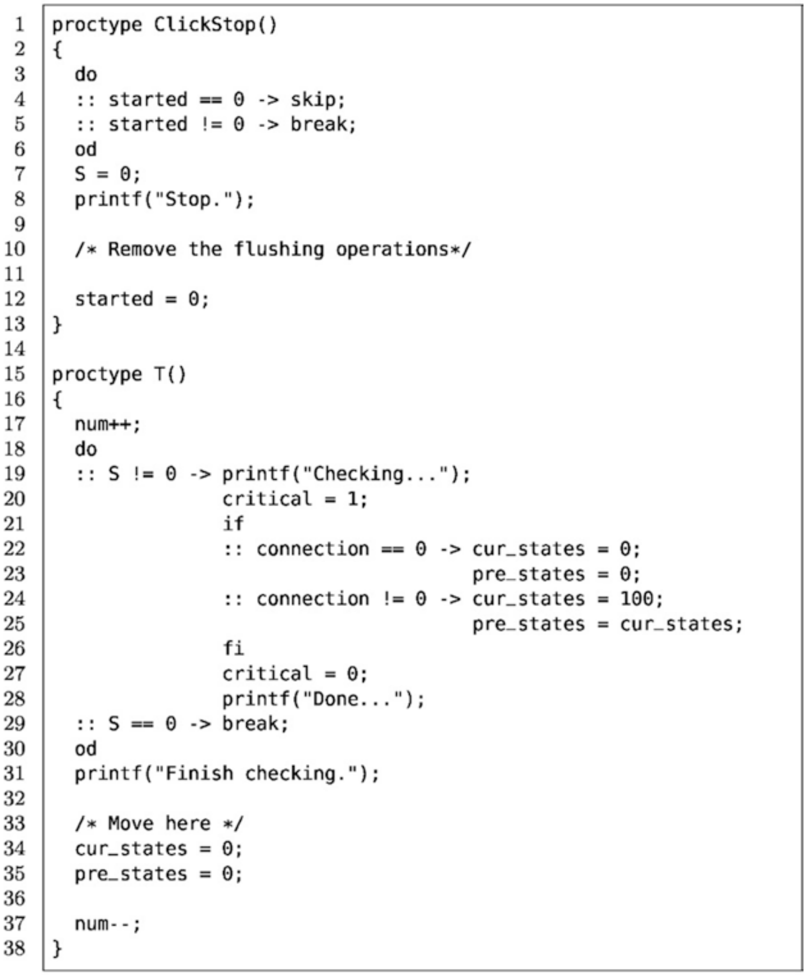
Fig. 8.14 The updated part in Design B

8.5.5 *Check Design B*

This section show the second iteration of the model checking procedure. After getting the "Design B" from the designers, we revise the model to reflex the updates. Figure 8.15 shows the updated model, called "Model B." Due to the page limitation, we only show the updated part of the model to show the difference between the current and the previous model.

We run Spin on "Model B" and find it passes the first and second properties. However, it violates the property 3, which indicates that multiple monitoring thread T() could run simultaneously. Similarly, we get a counterexample path from Spin. Due to the page limitation, we only describe the key point in the path rather than present the full-length path here. Briefly speaking, the property is violated when the user clicks the stop button and then quickly click the start button. Since in "Design B", clicking stop button enables all the input in the panel, users are able to click the start button before the monitoring thread T() exit. More specifically, when quickly clicking the start button after the stop button, the global variable S will be set to 0 and then set to 1 again. If this situation happens in one iteration of the loop in T(), the loop will not exit so the thread T() will not terminate. However, a new T() is started by ClickStart. Therefore, multiple monitoring thread T() are running in the TSM system, which violates the property 3.

Again, we reported the model checking results to the TSM system designers and they confirmed that this is a real bug. Multiple monitoring thread running simultaneously will cause the TSMS to send repeated tedious alarms. Moreover, in our counter example, there are only two T() running at the same time. In fact, this bug could cause much more T() running simultaneously, which could lead to a system crash. The designers carefully fixed the bug. They disabled all inputs in the panel until the monitoring thread T() exits. The fixed version is "Design C." Figure 8.16 shows the updated part in "Design C." The changed parts are ClickStop and T().



```
proctype ClickStop()
{
  do
  :: started == 0 -> skip;
  :: started != 0 -> break;
  od
  S = 0;
  printf("Stop.");

  /* Remove the flushing operations*/

  started = 0;
}

proctype T()
{
  num++;
  do
  :: S != 0 -> printf("Checking...");
               critical = 1;
               if
               :: connection == 0 -> cur_states = 0;
                                     pre_states = 0;
               :: connection != 0 -> cur_states = 100;
                                     pre_states = cur_states;
               fi
               critical = 0;
               printf("Done...");
  :: S == 0 -> break;
  od
  printf("Finish checking.");

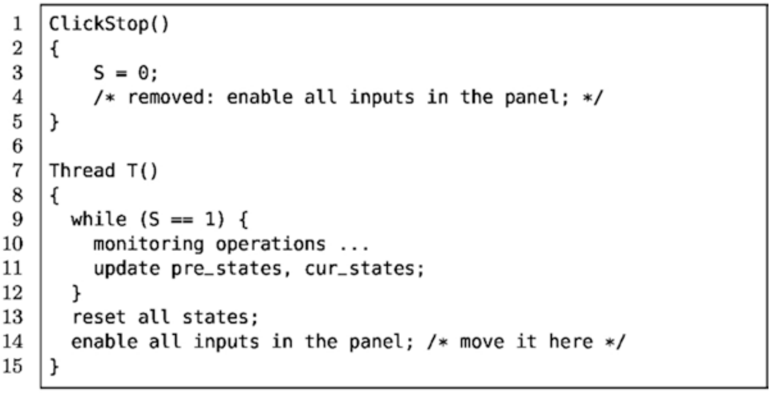
  /* Move here */
  cur_states = 0;
  pre_states = 0;

  num--;
}
```

Fig. 8.15 The updated part in Model B

8.5.6 Check Design C

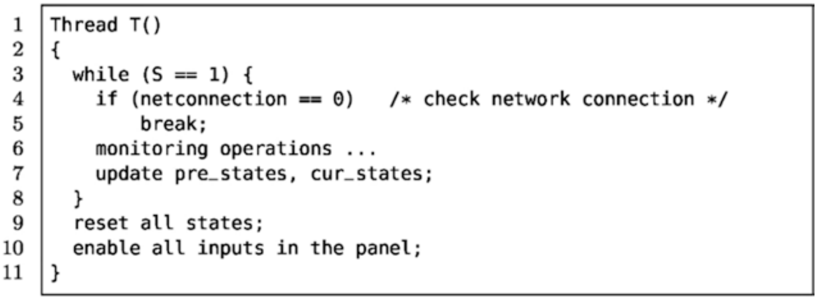
We repeated the model checking procedure on “Design C”. First, we revised the “Model B” according to the update in “Design C”. The new model is “Model C”. After that, we ran Spin to model check it. This time the first three properties passed but the last property failed. Similar to the previous sections, we obtained the output of Spin and reported it to the designers. Since the whole procedure is similar to the previous rounds of model checking, we skip the description of the steps and only describe the bug we found. The bug detected in the third round of model checking was the lack of network connection checking. When the network is disconnected, the TSM system runs as usual without sending any alarms. However, since the



```
ClickStop()
{
    S = 0;
    /* removed: enable all inputs in the panel; */
}

Thread T()
{
  while (S == 1) {
    monitoring operations ...
    update pre_states, cur_states;
  }
  reset all states;
  enable all inputs in the panel; /* move it here */
}
```

Fig. 8.16 The updated part in Design C



```
Thread T()
{
  while (S == 1) {
    if (netconnection == 0)   /* check network connection */
        break;
    monitoring operations ...
    update pre_states, cur_states;
  }
  reset all states;
  enable all inputs in the panel;
}
```

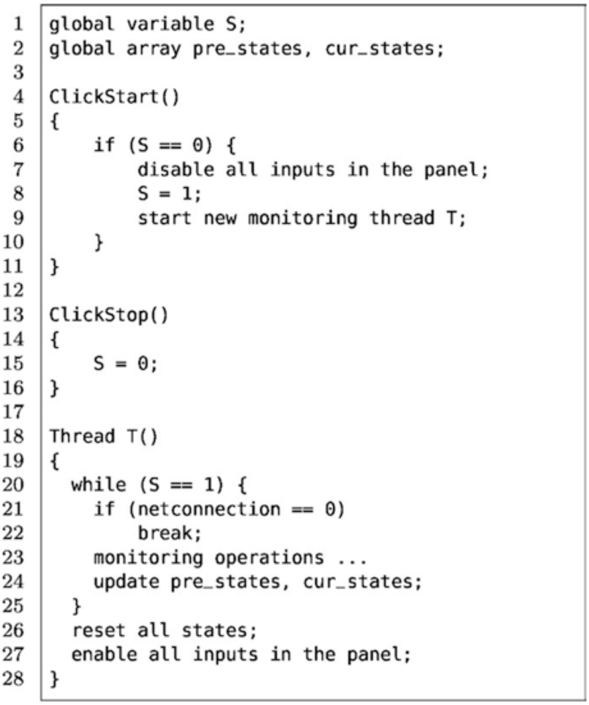
Fig. 8.17 The updated part in Design D

scaffold status is transmitted via the network, the TSM system could not check the status without the network. This bug could let users think the TSM system is running normally when the network is down, while the TSM system is actually not able to find any risk.

We reported the bug to the designers and they added network connection checking to the loop in T(). The updated version is "Design D" see Fig. 8.17.

8.5.7 Final Design

So far, we ran three rounds of model checking and improved the TSM system design iteratively. As before, we continued to update the model and model check the new model again. Finally, Model D passed all the properties checking. Therefore, as shown in Fig. 8.18, "Design D" is the final version during the model checking aided design procedure.



```
global variable S;
global array pre_states, cur_states;

ClickStart()
{
    if (S == 0) {
        disable all inputs in the panel;
        S = 1;
        start new monitoring thread T;
    }
}

ClickStop()
{
    S = 0;
}

Thread T()
{
  while (S == 1) {
    if (netconnection == 0)
        break;
    monitoring operations ...
    update pre_states, cur_states;
  }
  reset all states;
  enable all inputs in the panel;
}
```

Fig. 8.18 The final design of TSM system

8.6 Discussion

Generally speaking, we identified three bugs by iteratively model checking the TSM system as follows:

1. Multiple threads modify the same array without any lock.
2. Multiple monitoring threads are invoked simultaneously, which will cause racing problems.
3. The TSM system does not send any alarm when the network is down.

Since Spin is able to provide the counterexamples to trigger those bugs, the designers and we can easily reproduce them. Note that it significantly reduces programmers' workload, because usually reproducing a bug is the most difficult and time-consuming step when debugging a program. In our case study, the model checking tool prints the program path to reach each bug. We verified the path and then sent them to the TSM system designers. They found those paths were very helpful when trying to reproduce the bugs. The designers fixed each bug and patched the source code as follows:

1. Rewrite the ClickStop thread to avoid writing to the same buffer simultaneously.
2. Disable all inputs in the panel until the monitoring thread exits to avoid creating multiple monitoring threads.
3. Add a function to check network connection.

In this work, we acquired important experiences about model checking a cyber-physical system. First, we realized that critical bugs do exist in cyber-physical systems, even in those that look as simple as the temporary structures monitoring system in our case study. We really did not expect to detect three defects in such a simple system. The reason is that usually a simple system consists of a large number of states and paths, especially when the system involves concurrent execution. It is quite difficult for the designers to enumerate and track every path to see whether it will lead to a security problem. Model checking is exactly the approach to solving this problem. Modern model checkers such as Spin are able to enumerate, search and verify whether the model meets a set of properties in a very short time.

The second experience is the importance of the iterative model checking procedure. After each round of model checking, we returned the results to the designers, and they fixed it. We then updated our model accordingly and checked the new version again. The iterative model checking prevented the potential bugs introduced by the patch of the previous version. The repeated "checking-fixing" procedure gradually improved the design of the system.

8.7 Conclusions

Cyber-Physical Systems (CPS) have been widely used in different domains recently. The safety and robustness of CPS are becoming more and more important, attracting the attention of researchers. In this chapter, we presented a model checking method to verify and improve the design of CPS. In particularly, we used a temporary structures monitoring system (TSM system) as a case study. First, we worked with the designers to abstract the state transition system and properties. Second, we built a model to encode the TSM system and specification. After that, we ran the model checker to check whether the properties hold in the model. We reported the model checking results to the designers and they revised the original design accordingly. The model checking and revising procedure repeated until all properties held. During several rounds of model checking, the designers worked with us gradually to improve the CPS design. Our case study shows that model checking approach can help improve the design of CPS and reduce human labor.

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Chapter 9
Human-in-the-Loop Cyber-Physical Systems for Construction Safety

Sahel Eskandar, Jun Wang, and Saiedeh Razavi

9.1 Introduction

Construction industry, as one of the major economic sectors, has greatly benefited from automation and integrated systems. Ongoing advances in Computer Science and Engineering have led to the creation of stronger connections between the physical world and cyber space, which has assisted civil engineers in a variety of areas, from computer-aided design to automated operation of heavy equipment. Cyber-Physical Systems (CPS) are networks of tightly integrated physical processes with computation components, designed to monitor and control the physical world intelligently. CPS interaction with their operating environment is to measure and sense the environment and then process the information and act to achieve the desired outcome of the system. CPS uses networks of sensors and actuators to monitor and control physical phenomena and create environments that are highly monitored, easily controlled, and adaptable (Nunes et al. 2018).

CPSs has led to extensive applications in construction, some of which include controlling safety measures (Genders et al. 2016; Wang and Razavi 2019); visualization of a construction zone (Dawood and Mallasi 2006; Cheng and Teizer 2013; Guo et al. 2017); understanding the ongoing activities in working areas (Liu and Golparvar-Fard 2015); preventing contact collisions by issuing warnings to construction workers and equipment operators when there is a high probability of hazardous proximity (Genders et al. 2016); and enhancing the project delivery process in building and civil infrastructure development (Anumba et al. 2010).

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Cyber-physical systems reform how humans collaborate with the physical world by connecting the physical world to the cyber space (Rajkumar et al. 2010). Connection of cyber space to the physical world can be achieved through the integration of virtual models of the design and physical construction in a way that facilitates the bidirectional flow of information in the system. CPS environment usually contains human, and it has been argued that human need to be considered in the CPS framework since the majority of CPSs are working in favor of humans, and humans or users are essential parts of such systems (Cardenas et al. 2008; Munir et al. 2013; Nunes et al. 2018). Particularly in construction sites, where numerous employees and machines are working, moving, and interacting with each other in a complex and dynamic environment.

Moreover, involving a human in the loop of a construction cyber-physical system can make information acquisition more resilient (Cardenas et al. 2009; Leitão et al. 2016; Zhang 2017), and it is beneficial due to the lack of situational awareness as well as the excess of mental workload in a construction site (Griffor et al. 2016; Zhang 2017; Zhang et al. 2017). A CPS that takes a human into consideration is called Human-in-The-Loop Cyber-Physical System (HiLCPS or HiLCPS). HiLCPS achieves improved performance and accuracy by adding human to the control loop (Nunes et al. 2018). This can be in the form of incorporating aspects such as human intentions, behavior, presence, psychological state, emotions, and actions, which help better understand the context and determine actions that are more appropriate.

The human role in each HiLCPS can be identified based on the context, systems' goals, and the human-related factors that can affect the performance of the system. In this chapter, improving construction safety is the ultimate goal that is desired to achieve by implementing HiLCPS.

Improving construction safety has been a key concern due to the high rate of injuries and fatalities in the industry and the complex and unpredictable nature of the work (Molen et al. 2005). Accidents are happening in construction due to unsafe acts and conditions, for which human unsafe behavior and human error were identified as key contributing factors (Heinrich et al. 1980; Reason 1990; Chua and Goh 2004). Therefore, to design and develop an efficient HiLCPS for safety, it is important to identify conditions and causal factors leading to near misses, incidents, and accidents in construction.

In this chapter, different human roles in a HiLCPS are presented for improved design and development of such systems; particularly for safety in construction. Related human factors that are leading to unsafe behavior in construction are presented for inclusion in the future design of HiLCPS-based construction safety applications. Examples are offered for different stages of a HiLCPS for construction safety based on human physiological factors.

9.2 Human Role in HiLCPS

In order to fully understand the values and the concepts behind Human-in-The-Loop Cyber-Physical Systems (HiLCPSs), we need to study how humans can interact with a Cyber-Physical System (CPS). As it was mentioned in the Framework for Cyber-Physical Systems by NIST, CPS environment usually contains human; human might have different functions in the system based on the type of application, and the system architecture must consider different types of human interactions (e.g., human as a CPS controller, human as a user, human as a consumer of CPS result, and human as an entity to be monitored and receive actuation) (Griffor et al. 2016).

Based on the type of application, the human role and its position in the control loop might be different. Different taxonomies and frameworks for HiLCPS have been presented in the literature (Munir et al. 2013; Schirner et al. 2013; Griffor et al. 2016; Griffor et al. 2017; Nunes et al. 2018), from which we identified different roles that human could have in the HiLCPS for construction safety.

In the proposed framework for HiLCPS by Schirner et al. (2013), human's function was considered in connection with the embedded system (cyber space) and the physical environment. In the proposed framework, brain or body sensors collect information on human's conditions and intentions. Recorded and gathered information goes to the embedded system to be processed and be converted to a readable format by the physical environment. In the final step, the action is taken by actuators (Schirner et al. 2013).

Munir et al. (2013), categorized the human interactions with the HiLCPSs applications into three different groups: (1) Human directly controls the system, (2) System passively monitors humans, and (3) A hybrid of the two (Munir et al. 2013).

Nunes et al. (2018) proposed a taxonomy based on the role of humans in the system. In this taxonomy, the human was placed in different stages of the system, i.e., (1) data acquisition, (2) state inference, and (3) actuation. In other words, the human was considered to play a role in the system either by gathering data or providing status assessment or by acting in the actuation stage. Nunes' taxonomy for HiLCPS is aligned with what Griffor et al. mentioned about cyber-physical systems; "CPS can be seen as extensions of human capabilities, including sensing, decision-making, and action" (Griffor et al. 2017) (Fig. 9.1).

It should be noted that HiLCPS, as a type of cyber-physical system, resembles the CPS process. A basic conceptual model for CPS was proposed by NIST (Fig. 9.2). This model contains physical state, information flow, decision flow, and action flow. Human's interactions were considered in the proposed model by NIST, and CPS was assumed either as a single system or group of systems that is in connection with each other as a system of system (Griffor et al. 2016).

The human role in data acquisition stage in Nunes' HiLCPS model is comparable with the information flow in the NIST's model; similarly, state inference with decision flow, and actuation stage with action flow.

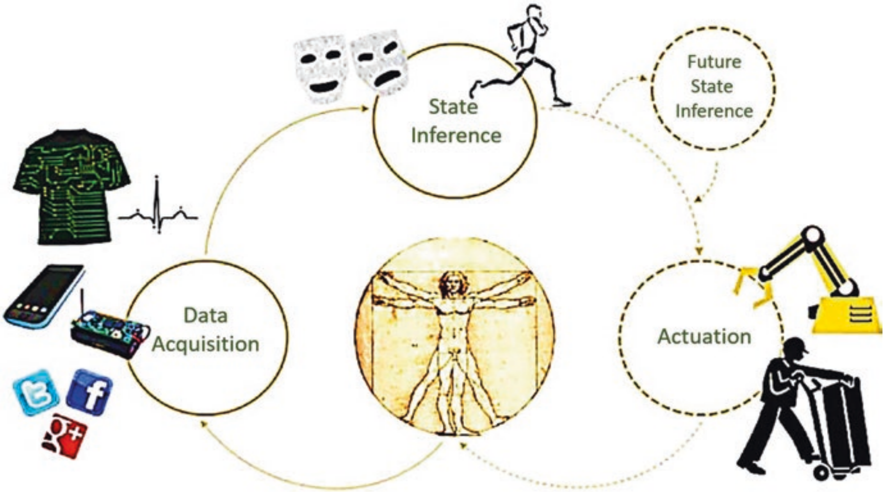

Fig. 9.1 Nune’s processes of human-in-the-loop (Nunes et al. 2018)

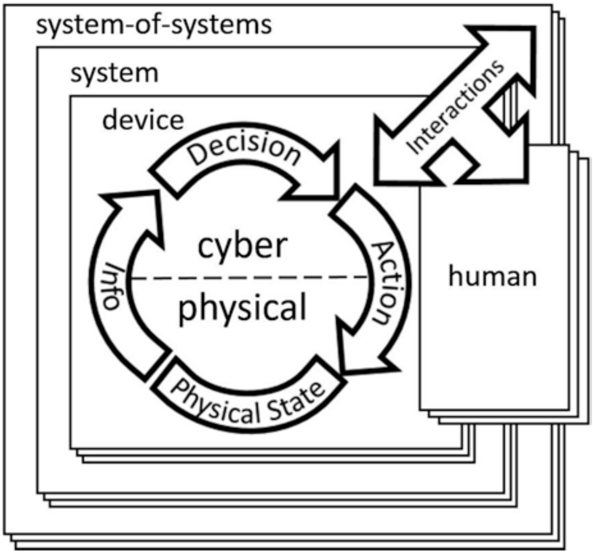

Fig. 9.2 CPS conceptual model [15]

In addition to the data acquisition, state inference, and actuation process mentioned by Nunes et al. (2018), feedback control needs to be considered in a HiLCPS conceptual model. Feedback control is required to enable the system to well-adapt itself to the new physical conditions and unpredictable circumstances. Thus, a feedback stage is an essential part of the HiLCPS (Lee 2008; Munir et al. 2013; Griffor

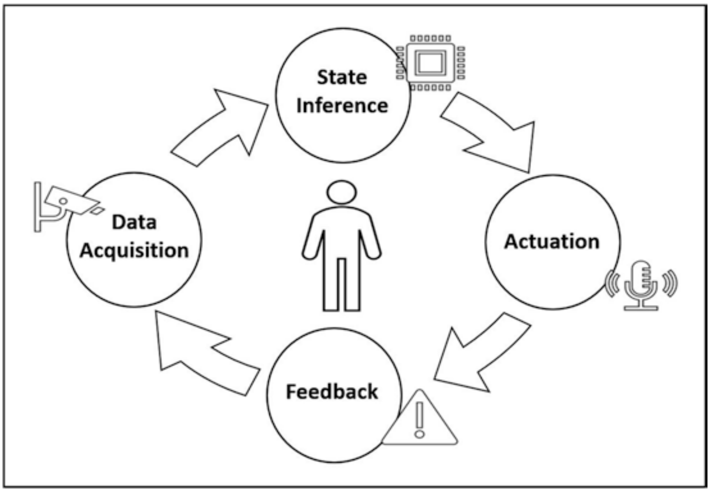

Fig. 9.3 Human role in HiLCPS

et al. 2016; Guan et al. 2016; Zhang et al. 2017), in which human can contribute to enable the system to be more adaptive and efficient.

Figure 9.3 depicts different procedures where a human entity can contribute to the CPS. The HiLCPS loop demonstrates different ways that human can participate in the system and function.

Human can contribute to the data acquisition process by directly providing the system with data or by carrying sensors such as smartphones or wearable devices. Input to the system could be even by human activities in social media or a message conveyed by a human on behalf of the system (Nunes et al. 2015; Nunes et al. 2018). Information transmission conducted actively or passively by a human would be the form of human interactions with the system in the data acquisition process.

State inference, as the next stage within HiLCPS loop, is related to the human contribution in the assessment of situations. This process recognizes human situational awareness, cognition, physiological status, or psychological states. Human in this stage can provide the system with processed information.

Actuation in HiLCPS loop could be as simple as an instant notification to alert a user. Human's direct contribution in actuation step is considered when there is a necessity for specific human action rather than actions from systems or robotic actuators. In HiLCPS, human and machine actuation can assist each other in different situations, and their function can be supplementary.

As stated earlier, feedback control and the possibility of human contribution in this step need to be considered in the HiLCPS loop. Controlling some part of the system, such as changing a parameter in the system in order to reach the desired outcome is an example of incorporating human into feedback control. Human contribution in this process will result in a more reliable and robust system (Munir et al. 2013).

Human as a central part of cyber-physical systems can be placed in any of the anticipated stages based on the type of application and the context. For incorporating human in each application, understanding related human factors and parameters in favor of the system objectives are necessary. For designing and developing a HiLCPS to eliminate unsafe act in construction, identifying and recognizing human factors leading to an unsafe act is exceptionally vital.

9.3 Human Role in HiLCPS-Based Construction Safety Applications

Human-in-the-loop (HiTL) applications have been used in broad areas. In the construction domain, several types of research and experimental projects have been carried out to consider human as a component in the system (Marks and Teizer 2012; Zhang 2017; Zhang et al. 2017). In considering human as a part of a system, capturing human's attributes is particularly challenging due to the complex nature of the human (e.g., physiological, psychological, and behavioral) (Stankovic 2014). Identifying human factors related to the safety in construction is necessary for integrating the human into the cyber-physical systems.

In Eskandar et al. (2019), the authors studied and presented social, physiological, and cognitive human factors that influence safety in construction. These three major categories of construction safety factors were synthesized to guide the research and practice. For achieving safe conduct from a social perspective, improving safety climate and social norms have been suggested. From a physiological perspective, body posture, fatigue level, and stress have considered being responsible for unsafe behavior. Suggested physiological conditions (i.e., threatening body posture, excessive fatigue level, and stress) can be identified through relating bending angel, heart rate, energy expenditure, and oxygen consumption. Moreover, studying individual cognition and team cognition has been suggested in understanding the reasons in taking an unsafe act.

Additionally, regarding physiological factors, the following ergonomic risk factors presented by Jaffar et al. (2011) can contribute to an injury among construction workers. Awkward posture (excessive bends or twists), force (physical effort), repetition (over-extension and overuse of specific muscle), vibration (body movement at a fixed point), static loading (one postural position for an extended duration), contact stress (injury by hard and sharp objects), and extreme temperature (extremely cold and hot), are defined risk factors that increase the risk of injury to the musculoskeletal system among construction workers. These ergonomic risk factors need to be prevented to improve safety in construction.

Considering the human factors affecting the safety in construction, the role of the human in HiLCPS-based construction safety applications can be summarized as below. In the following sections, examples are offered for different stages of a HiLCPS for construction safety based on physiological factors.

9.3.1 Human Role in Data Gathering

Data acquisition as the first stage of a HiLCPS control loop provides required data for the system functionality. Human involvement in this stage assists in collecting data on physical phenomena such as body temperature or heart rate, or nonphysical events such as social media posts, or human's contact list. Such types of data collection enable the system to further identify patterns of activities, human's physiological or psychological states, and the external conditions. Due to the dynamic and complex nature of construction jobs, suitable sensors, and data gathering methods should be chosen carefully to avoid disruptions to the nature of the job and distraction for the workers. One of the efficient and non-disruptive ways of collecting data is by using Wireless Sensor Networks (WSN) with the support of data streaming services (Wood and Stankovic 2008).

With advances in wearable sensors, it became easier to collect real-time information in an undisruptive manner. Human vital signs such as body temperature, blood pressure, heart rate, respiratory rate, in addition to oxygen level, and sleep pattern can simply be recorded through wearable body sensors and health gadgets (e.g., smartwatch, bracelets, earbuds, smart clothes, smart fabrics, headset, smart socks). Moreover, electrophysiological signals such as electroencephalography (EEG), electrocardiography (ECG), electromyography (EMG), which are electrical activities in different parts of the human body can be measured through body and brain sensors (Schirner et al. 2013). Measuring electroencephalographic signals (EEG) that are electrical activities in the brain and recording brain activity can help us in identifying intentions (Lew et al. 2012) and emotions (Chanel et al. 2006).

In addition to various types of body and brain sensors, smartphone as a powerful and ubiquitous device allows effortless and passive data collection. Smartphones contain multiple embedded systems and sensors, which are capable of monitoring and recording human activities as well as processing the recorded information. Involving smartphones at the extreme edge of the network brings the idea of fog computing (smartphones as edge nodes). Fog or edge computing will help to increase awareness of the system by analyzing data close to the place it is gathered (i.e., edge devices) instead of sending it to the core network (i.e., cloud data center) (Bonomi et al. 2012; CISCO 2015). In this way, human's collaboration with CPS is by not only sharing collected data through smartphones (i.e., data collection stage) but also by sharing the knowledge gained through their computations and inferences (i.e., state inference stage) with the system using their cellphones.

9.3.2 Human Role in State Inference

State inference is generally about processing data to infer human intent from the collected information. For most HiLCPSs, different mathematical models or machine learning options would be adopted to detect the system's or human's states.

Human role in state inference could be through offering direct information or knowledge to the system that results in saving much effort and time (Nunes et al. 2018). Research studies also infer that human perception and cognition is still more reliable and accurate than current algorithms and computations (Schirner et al. 2013).

However, it is worth mentioning that due to the limitations associated with the nature of human beings and the related costs of human involvement in the state inference stage, human involvement has been restricted in some applications like Intelligent Surveillance Systems (ISS). In such cases, instead of human collaboration, intelligent algorithms, image processing techniques, pattern recognition, and artificial intelligence have been used for data processing (Dautov et al. 2018).

9.3.3 Human Role in the Actuation Process

Based on the type of the identified state in the state inference stage, actuation may take place to change the physical environment according to the desired goals of the system. Actuation could also happen simply by providing information or warnings. As an example, in a fall detection system, the worker's physical information could be recorded using an accelerometer. Detecting a rapid change of acceleration in the vertical axis can be considered as a fall. Once a fall is detected through the data gathering and state inference, an instant alarm and notification may be generated, in the actuation stage, to report the fall to the safety controller, medical emergency services.

9.3.4 Human Role in the Feedback Process

To have a reliable, robust, and adaptive system, there is a need for a feedback process in HiLCPS loop. The feedback process observes the monitored phenomena or environment and provides input to the system if further actions are required.

It is also noteworthy that the system in its lifecycle may face some changes or challenges that might prevent it from performing in its best way (e.g., changes in the user's preferences). Human and user feedback can improve the system and can direct it toward the desired outcomes. For this aim, the system can support and learn from human observation, preferences, and decisions in addition to the self-adopting process (Liu et al. 2011).

9.4 Examples of Human Roles in HiLCPS-Based Construction Safety Applications

Construction work as a physically demanding job typically alters workers physiological state, which may lead to unsafe conditions. Physiological factors contributing to unsafe acts or conditions need to be gathered by non-disruptive monitoring systems. This section presents some examples of HiLCPS for construction safety based on physiological factors. Examples are mainly focused on the data gathering and state inference stages as the most fundamental and essential phases in the design and implementation of a HiLCPS.

As previously mentioned, from a physiological perspective, body posture, fatigue, and stress have been identified as contributing factors for accidents (Eskandar et al. 2019). Associated data related to each of these factors need to be gathered (i.e., data gathering) for the unsafe action or condition to be identified (i.e., state inference). Upon detecting an unsafe state, appropriate actions will be taken (i.e., actuation), and the system will continue to observe the state until a safe condition is achieved (i.e., feedback). Below are examples of how some of the commonly recognized unsafe states for construction workers can be identified to be acted upon.

9.4.1 Bending Posture

For monitoring workers bending posture and preventing unsafe postures, observing worker's bending angle and location can help to identify harmful activities and the associated location. Accelerometers can be used for collecting tri-axial accelerations, which will proceed using posture analysis (Lee et al. 2017). Data extracted from accelerometer and motion sensors are capable of tracking movements, recognizing activities, and distinguishing action pattern (e.g., rotation angles, joint angles, position vectors, and movement direction) (Han et al. 2013), which can be used to detect and prevent hazardous activities associated with ergonomic risk factors.

9.4.2 Fatigue

Fatigue can be identified and predicted through recording sleep patterns (sleep deprivation) (Powell and Copping 2010), neuronal activity (decline in the central and peripheral nervous system), and cardiorespiratory metrics (Techera et al. 2018). Forceful or extended physical activity, especially in the high temperature, may result in fatigue that can be determined by measuring and controlling the heart rate, blood oxygen level, blood pressure, respiratory rate, and body temperature (Bates and Schneider 2008). Besides, a human can directly provide input to the system on related fatigue symptoms such as drowsiness and dullness, difficulty in concentration, and projection of physical impairment (Chang et al. 2009).

9.4.3 Stress

Ten different work-related job stressors that result in either injury or near misses among construction laborer were identified by Goldenhar et al. (2003). Various physical and emotional stress symptoms among construction workers were presented by Liang et al. (2018) that could be useful in gathering data for identifying stress. This study identified physical stress symptoms as physical pains, skin diseases, eye strain, respiratory illnesses, prostate problems, dizziness, loss of appetite, and sleep disorders; and emotional stress symptoms as anxiety, anger, tension, listlessness, and worry. In another study, for recognizing stress, electroencephalography devices (EEG) have been used to record construction workers' brain activity (Jebelli et al. 2018). Moreover, in addition to destructive effects of stress among construction workers, according to a study on Chinese construction workers, workers with depressive symptoms have a higher risk of work-related injuries (Zheng et al. 2010) that need to be monitored.

HiLCPSs-based construction safety applications can automatically sense and monitor physiological factors and consequently identify and control unsafe human actions and conditions in a complex and active environment of construction (Gualdi et al. 2009). From a physiological perspective, bending posture, fatigue, and stress are contributing to unsafe acts and states. Base on the type of HiLCPS-based application, the associated data needs to be collected (e.g., workers tri-axial acceleration for posture analysis detection). Then, by processing the collected data and identifying the corresponding condition (e.g., calculating bending angle or observing fatigue symptoms), appropriate action can be taken to improve safety in construction.

9.5 Conclusions

Human-in-The-Loop Cyber-Physical System (HILCPS) considers human in the system in addition to the cyberspace and the physical environment. Human, as a central component of HiLCPS, may have different roles and interactions in the system. The human involvement can be at each stage of the HiLCPS loop, i.e., data acquisition, state inference, actuation, and feedback.

HiLCPS can be used for construction safety, where safety-related factors, such as physiological, social, and cognitive human factors can be more efficiently monitored and controlled.

Different types of body and brain sensors or even smartphones can be used in the data-gathering stage to gather various data in a non-disruptive way. In the state inference stage, human perception and cognition can be used instead of complex computational procedures such as artificial intelligence or machine learning. In the actuation step, a human can manually act to change the physical environment, and for enhancing the system, a human can send feedbacks to improve the desired outcomes of the system.

HiLCPS has the potential to improve construction safety by reducing unsafe actions and conditions. Advances in sensing and wireless communication technologies are enablers for a successful implementation of such systems. However, the challenge will remain in identifying all contributing factors to construction safety and their associated data types as well as determining efficient ways to capture, process, monitor, and control those factors.

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Chapter 10
Cyber-Physical Systems (CPS) in Intelligent Crane Operations

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10.1 Introduction

Cranes are arguably the most important, if not indispensable, type of machinery in most construction projects, ranging from residential and commercial buildings to railway, bridges and industrial plants. Compared to the operations of other types of machinery, crane operations present unique characteristics with respect to spatial and temporal scales. The workspace of cranes, especially for tower cranes, is massive, covering the majority of the construction site. Cranes are usually in service throughout the entire period of construction, responsible for the majority of lifting activities. The first known construction crane traces back to ancient Greece, where cranes were powered by the physical exertion of men or animals. The introduction of combustion engines and hydraulic systems significantly strengthened the lifting capacity and improved the productivity of modern cranes. While lifting capability is no longer the main limitation of crane lifting performance, the new challenge lies in the efficient and safe operation of cranes in the increasingly dynamic and complex construction environments. For example, new construction methods such as

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modular construction in residential, commercial and industrial projects with increased usage of cranes during on-site assembly require a higher level of precision in the planning and operation of cranes.

Crane lifting operations are inherently a sophisticated job that imposes significant mental workload on crane operators. During the lift, a crane operator needs to continuously monitor the environment changes such as wind speed and the presence of foreign objects (e.g., unauthorized equipment and personnel), based on which the operator adjusts the crane maneuver speed or alters the lifting strategy. At the same time, the operator has to understand the crane's capacity and status using the load chart, boom angle indicator, or load moment indicator (LMI). In addition, lifting operations usually involve the coordination with the riggers or signal people. However, the information the operator receives from these sources is not always accurate or complete due to various reasons such as obstructed line-of-sight, poor communication or misunderstanding. Consequently, it is not surprising to find that 43% of the crane related accidents occurred from 2004 to 2010 in the US were due to operator errors (King 2012). Therefore, there is a pressing need for computer-aided intelligence in crane operations to augment the operator's abilities to understand the lifting tasks and environment, to recognize safety and efficiency barriers, and to make timely decisions and right actions to address the barriers.

Intelligent crane operations refer to a computer-aided, human operated process. An intelligent crane system (ICS) is expected to capture relevant on-going crane operation data, to analyze safety and efficiency conditions based on the data, and to guide the human operator to make improving decisions and actions. It is not hard to find that the requirements for intelligent crane systems can be well satisfied by embracing a Cyber-Physical Systems (CPS) framework. A CPS integrates computational resources with physical processes and establishes bidirectional coordination between the cyberspace and the physical world. CPS allows a sensing-analysis-feedback loop to complete in real or near-real time in the dynamic crane operation environment. Naturally, A CPS framework becomes a suitable and necessary foundation for intelligent crane systems.

This chapter presents an overview of current applications and future potentials of CPS in intelligent crane operations. It starts with a review of existing technologies that are used on modern construction cranes and then presents a general CPS framework for intelligent crane systems. This is followed by a description of the main tasks for a CPS-based intelligent crane system (CPS-ICS) and the key enabling technologies to accomplish these tasks. It concludes with a discussion of other necessary technical components for CPS-ICS.

10.2 CPS Framework for Intelligent Crane Operations

After having described the safety and efficiency challenges in crane operations and the necessity of CPS in intelligent crane operations, this section presents a high-level CPS framework for intelligent crane operations, as shown in Fig. 10.1. This

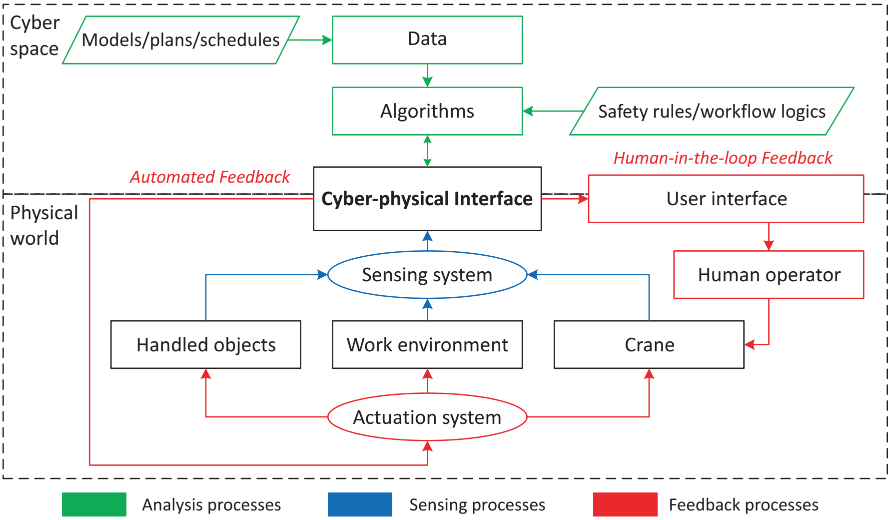


Fig. 10.1 A high-level framework for CPS-ICS

framework consists of components, entities, and processes in the physical world and the cyber space. A cyber-physical interface enables bidirectional communication between the physical and cyber components. The two cyber components are Data and Algorithms. The Data represents any project related data and information that are relevant to the crane operation. These data can be of different formats and sources (e.g., models, plans, schedules) and can be stored externally to the CPS system. The Algorithms represent the processing and computation of data that are needed to perform certain tasks for safety and efficiency analysis. For instance, the task of collision detection requires the algorithm(s) to consider all applicable safety rules (e.g., clearance, speed, crane load chart) and flag collision risks based on the input data from the models and the sensing system. The physical components include typical operational entities: Crane, Work Environment, Handled Objects, as well as CPS-specific entities: Sensing and Actuation Systems. Work Environment refers to the physical conditions within the crane workspace, including environmental conditions (e.g., wind speed, ground support), spatial constraints (permanent and temporary structures, power lines), and the dynamics of moving objects (e.g., workers, vehicles, machinery). The sensing system is to capture the changing states of the crane, the handled objects, and the work environment and to feed this real-time data to the algorithms in the cyber space for analysis. Instructions based on the analysis results such as performing a new lift path can be executed via two modes of control feedback: autonomous feedback and human-in-the-loop feedback. In autonomous feedback mode, instructions are automatically executed through the actuation system to change the states of the entities. In human-in-the-loop feedback mode, instructions are presented to the human operator via a user interface. The operator is responsible for interpreting the information presented by the system, based on which to make decisions and actions.

10.3 Main Tasks and Key Enabling Technologies in CPS for Intelligent Crane Operations

It is important to identify the main tasks and key enabling technologies for CPS in crane operations, so that we can benefit from incremental advancements of technology. The following sections present four fundamental tasks expected from CPS-ICS: (1) crane and load state sensing, (2) work environment modeling and updating, (3) safety and efficiency analysis and planning, and (4) control feedback. For each task, multiple state-of-the-art technologies are discussed with a review of their current implementation and future potential in intelligent crane operations.

10.3.1 Task 1: Crane State Sensing

The first and most important task in intelligent crane operations is to understand the states of the crane and the payload. Traditional crane computer systems such as load moment indicator (LMI) mainly investigate crane's lift capacity in optimal conditions (e.g., no wind, level and firm ground). Other critical dynamic factors such as inertia effects and payload swing that significantly contribute to the stability of the crane are usually not considered. Capturing crane motions in real-time is essential for analyzing the crane capability and stability, as well as its interaction with the surrounding environment. Basic requirements for technologies used to capture crane motions include accuracy, precision, robustness, low-latency, scalable, and non-intrusive to the crane itself or other tasks related to the crane operation. The key technologies for the task of crane and load state sensing are introduced in the following sections, including real-time location systems, computer vision, laser scanning, and kinematics analysis and encoder sensors.

Real-time location systems (RTLS) are technologies that track the location of tagged objects in real-time. In construction, RTLS technology has been used for site security, resource location tracking, and equipment safety. In crane operation domain, Luo et al. discussed the requirements for autonomous crane safety monitoring and envisioned the requirements and strategies to leverage RTLS technology for autonomous crane safety monitoring (Luo et al. 2011). To estimate mobile crane poses in near real-time, Zhang et al. employed a high-precision RTLS technology named Ultra-wide band (UWB) with UWB readers deployed around the lifting site and UWB tags mounted on different spots of crane boom and payload (Zhang et al. 2012) (Fig. 10.2). Using a similar technology, Hwang studied the characteristics of different collision types and developed a computer program for monitoring crane motions and sending warnings if a potential collision hazard was detected (Hwang 2012). Li et al. took advantage of the Global Positioning System (GPS) and Radio Frequency Identification (RFID) for a real-time crane motion monitoring system (Li et al. 2013). Tracking crane parts and construction workers, this system aims to assist the safety operation in blind lifts by detecting the presence of unauthorized

(a) Boom tip (b) Hook

(c) Lift object (d) Hardhat

Fig. 10.2 UWB sensor and tag deployment for crane motion tracking (Zhang et al. 2012)

workers within a risk zone. Luo et al. analyzed the impact of RTLS sensor errors on autonomous crane safety monitoring (Luo et al. 2014). They proposed a three-level safety zone for incorporating RTLS-based location data in the identification of wing-above-worker incidents. Although these efforts demonstrated the feasibility of using RTLS to monitor crane and load states, the RTLS technology suffers from several limitations including (1) sophisticated sensor system setup, (2) signal interference in harsh construction environments, and (3) high cost for RTLS with higher accuracy (e.g., UWB).

Computer vision techniques extract high-dimensional data from digital images or videos. Recently, the construction research community began to embrace the benefits of computer vision techniques in equipment operation applications. Feng et al. introduced a marker-based computer vision approach that uses a set of cameras and markers to identify the pose of articulated equipment (Feng et al. 2015). With at least two cameras and multiple planer markers on each of the articulated part and a pre-survey fixed location near the equipment (Fig. 10.3), this method was able to yield centimeter-level tracking accuracy with a flexible and cost-effective system. Although this method performed well in tracking the pose of an excavator in a small workspace, limitations such as sensitivity to occlusions and increased

Fig. 10.3 Computer vision techniques for equipment pose estimation: maker-based (Yang et al. 2013) and machine-learning based methods (Roberts et al. 2017)

complexity in system setup can be expected when applying this method to track crane states on a much larger scale and more dynamic workspace. Yang et al. proposed an algorithm to track the job pose of a tower crane by processing and analyzing the images captured by a single site surveillance camera (Yang et al. 2013). With the known locations of the surveillance camera and the configuration of the tower crane, a set of synthetic images were generated using a virtual 3D model of the crane. The crane poses in actual images can be identified by comparing them to the synthetic images. This method requires pre-surveying the location of the camera and crane, which is possible for tower crane settings but is challenging for mobile crane setting as the system needs to re-setup every time the mobile crane relocates. The increasing availability of UAVs (Unmanned Aerial Vehicles) with high-definition cameras offers a new way to monitor crane states. Robert et al. used a convolutional neural networks (CNNs) algorithm to automatically detect cranes and their parts from UAV-captured site images (Roberts et al. 2017). Using this method, crane poses can be estimated accurately in real time, which makes it possible for end-to-end machine vision applications such as payload tracking or 3D crane pose estimation (Fig.10.3). Despite promising progress in equipment pose sensing, computer-vision based methods suffer from several limitations including prevailing visual noise and occlusion, limited coverage, poor performance at low lighting and visibility conditions, and rather low reliability (Azar and Kamat 2017).

Laser scanning is a non-intrusive sensing technology that rapidly and accurately captures the 3D shape of physical objects in the format of a point cloud. To help equipment operators rapidly perceive the crane pose and surrounding environment, Cho and Gai introduced a dynamic object recognition and registration method using laser scanning technology (Cho and Gai 2014). The 3D point cloud is projected to a 2D space where the geometric features represented by a local SURF descriptor are compared to a prepared template database for recognition. This method is effective and efficient for recognizing target objects that are known to be present on the construction site. Wang and Cho proposed a smart scanning technique for tracking the location and pose of mobile cranes (Wang and Cho 2015). By updating the crane's point cloud data while keeping the previously scanned static workspace data, this method greatly improves the modeling and updating rate, which makes it suitable for real-time visualization and decision-making support (Fig. 10.4). Another benefit of laser scanning-based approaches is that it is non-invasive, meaning that there is no need to deploy any sensors or devices on the equipment. Instead, it requires a data acquisition system to operate in proximity to the equipment, and sophisticated infrastructure setup for real-time data processing and transmission.

Rotary encoders are electromechanical devices that are used in various electronic and mechanical devices for measuring angular position or motion of a shaft or axle in the device. From a kinematics perspective, a crane can be understood as an entity comprised of multiple rigid bodies connected by different types of joints, depending on the crane type and configuration. For example, a typical telescopic boom mobile crane can be decomposed into two independent modules: the manipulation module and the suspension module (Fig. 10.5). The manipulation module is comprised of three rigid bodies including a truck base, a crane body, and a telescopic boom. The suspension module consists of a normal rigid body, the lifted load, and an extensible rigid body for the hoist line. The connections between the rigid bodies can be modeled by three types of joints: revolute joint, prismatic joint and spherical joint. This simplification makes it possible to represent any possible crane pose by measuring the critical angle or length of a particular joint that connects every two rigid bodies. Lee et al. proposed a crane motion monitoring system using multiple encoders and laser sensors, which successfully captured and visualized the motion of a tower crane in real-time (Lee et al. 2012a). However, this system does not consider the load sway, and the configuration of a laser sensor and reflection board cannot reliably measure the load elevation during excessive load sway. To improve Lee et al.'s approach, Fang and Cho proposed a mobile crane motion capturing system using rotary encoders and inertial measurement unit (IMU) sensors (Fig.10.5). The IMU sensor mounted on the crane hook measures the load 3D orientation. The orientation is then converted by a transformation matrix to a 3D

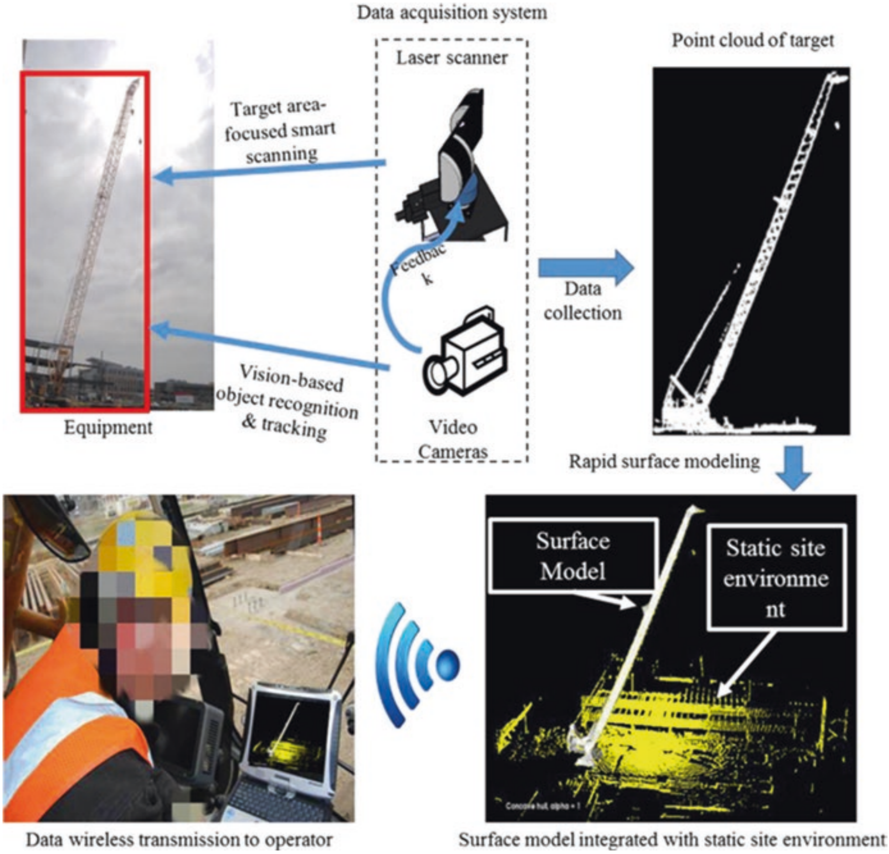


Fig. 10.4 Smart scanning and modeling of a crane in near real-time (Wang and Cho 2015)

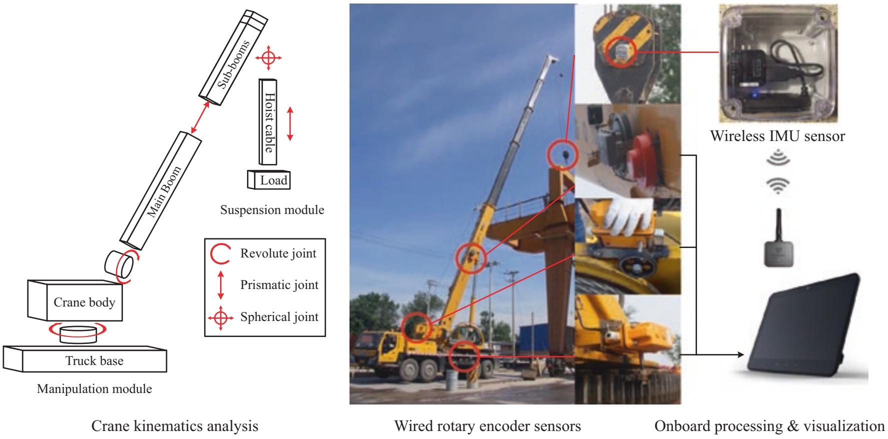


Fig. 10.5 Kinematics analysis and an encoder sensor and IMU -based crane state sensing system (Fang et al. 2016)

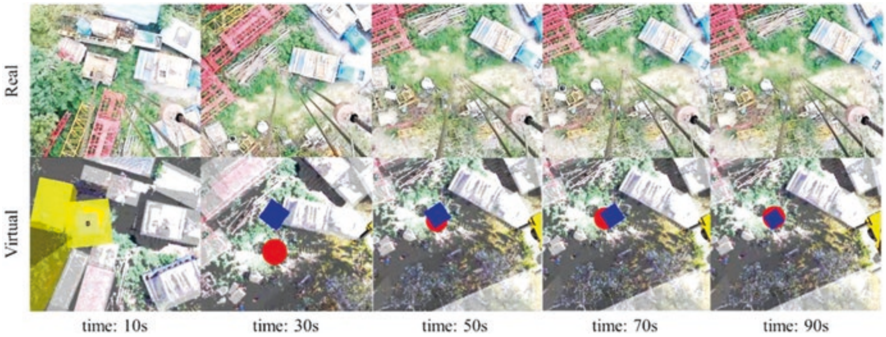


Fig. 10.6 Comparison between actual and reconstructed sway motions (Fang et al. 2016)

position relative to the boom tip. Using this approach, the load sway can be captured and visualized in real-time (Fig. 10.6). The framework was validated by a prototype deployed on a real crane and a field test was conducted to evaluate the system performance with respect to reconstruction accuracy, timing, hazard analysis and visualization effectiveness. Test results indicate that the prototype system was able to reconstruct crane motions with an average error of 0.43 m for real-time load positioning. It also proved that the system is effective in providing pro-active hazard warnings that allow the operator to make timely decisions to mitigate the risk. Compared to the RTLS-based and camera-based crane monitoring methods, the direct motion capturing method hold several advantages. Firstly, the hardware employed in the systems is usually more cost-effective and durable in long-term use. Once securely installed on the crane, the sensors require little maintenance and with proper enclosure they can work properly in harsh environmental conditions. Secondly, sensor-based methods do not require external hardware deployment on the site, and thus it introduces minimal interruption to other construction activities.

10.3.2 Task 2: Work Environment Modelling

The second major task for CPS-ICS is to model the work environment. Cranes' lift capability and maneuverability can be greatly affected by the spatial constraints in the surrounding environment, especially for mobile cranes as their location and workspace change quite frequently as project proceeds. This makes it very difficult for operators to be fully aware of the dynamic context and temporal constraints of the site environment, thereby resulting in potential safety hazards and operational inefficiencies. This section discusses several technologies that are useful for modeling the crane work environment.

Building Information Modeling (BIM) is a process for creating and managing all the digital representations and information of the physical and functional characteristics of a construction project. In the task of modeling crane work environment, BIM has the potential to provide information including the site layout and detailed models of the building structure that are useful to model the geometry of the crane workspace (Lee et al. 2012a). A BIM model also contains construction schedule data (4D BIM) that makes it possible to model the crane work environment at different construction stages based on the construction sequence (Wang et al. 2015). Nevertheless, using only BIM to model the work environment is not adequate. Design changes occur throughout the planning and construction phases, and thus geometry obtained from a BIM model may be outdated and no longer represents all up-to-date geometric constraints existing in the actual work environment. Therefore, in addition to a BIM model and other as-designed plans, an effective CPS-ICS needs to model the as-built conditions of the work environment in real-time. As introduced in Sect. 3.1, ***Laser Scanning*** technology is capable of capturing the 3D geometric data of the surrounding environment in a short period of time. The resulting point clouds, after a pre-processing pipeline, can be used to reconstruct the scene efficiently by using oriented bounding boxes (Fang et al. 2016). Laser scanning is not the only method that can generate the 3D point cloud. ***Structure from Motion (SfM)***technology reconstructs 3D point clouds from large sequential and unordered collections of images captured by hand-held or drone-mounted cameras. Although point clouds obtained by SfM technology is less dense and accurate than laser scanned point clouds, using the as-designed 3D model as a priori can significantly improve the SfM performance by reducing rotational and drift errors, producing a more accurate and detailed point cloud (Karsch et al. 2014).

10.3.3 Task 3: Mobile Asset Tracking

During the lift operation, the crane interacts with not only the static obstructions in the surrounding environment, but also the mobile assets (e.g., equipment, workers, materials) present in the work environment. These mobile assets could be directly involved in the lift operation (e.g., rigging crew, delivery truck) or simply share the workspace with the lift operation (e.g., nearby excavation operation). No matter which cases, it is important for the CPS-ICS to incorporate dynamic context by detecting the existence of these objects and tracking their locations and moving patterns.

In the construction engineering domain, ***RTLS (real-time location systems)*** has been extensively investigated as a promising technology to localize construction workers, equipment, materials in the construction site environment (Lee et al. 2012b). Among various RTLS technologies, active RFID (Radio-frequency identification) technology is deemed most suitable for tracking construction assets in a construction environment (Li et al. 2013). The active RFID tags have many advantages: they are very cheap so that they can be applied for every asset in large-scale construction sites (Li and Becerik-Gerber 2011); they are small, thin, and flexible that can be easily attached to the asset, without the need for re-design and extensive retrofitting. In traditional use, each active RFID tag is assigned a unique ID and

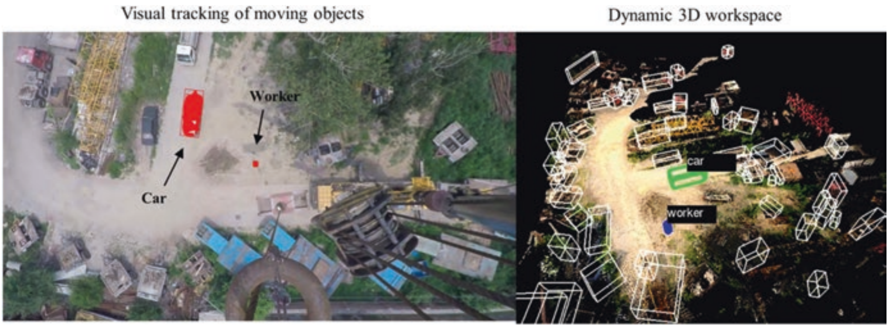


Fig. 10.7 Object tracking and 3D workspace updating in a crane workspace (Chen et al. 2017)

stores different data to be read by the RFID receiver. Recent research attempts to exploit properties of the underlying physical-layer signals from tags, such as phase, amplitude, polarization, waveform, coupling effect (Liu et al. 2017). These signal properties carry far-richer information that can be exploited to determine the objects' orientation, location, trajectory, spacing, speed, and oscillation. Luo proposed to use RFID to track the location of workers in an autonomous crane safety monitoring system (Luo et al. 2011). Combined with GPS (Global Positioning System), active RFID technology was used to monitor struck by-related safety risks during crane operations (Li et al. 2013).

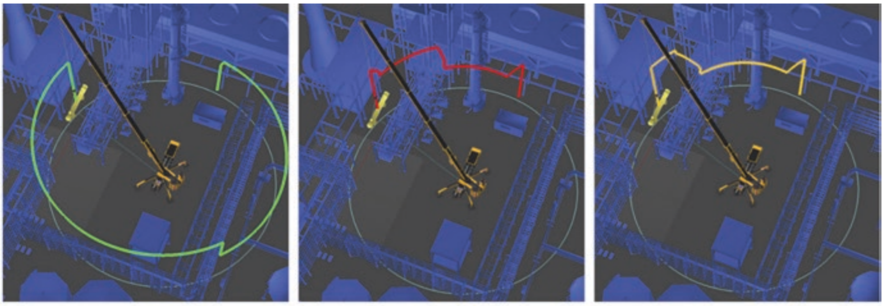
Over the past decade, many ***computer vision***-based approaches have been developed with the purposes to detect and track the objects of interest from visual data (e.g., images and videos) (Yang et al. 2015). Many of them have been proved to work fairly well in complex construction environments (Teizer 2015). However, the biggest limitation of computer vision-based detection and tracking methods is that they require line-of-sight between the cameras and the object. One solution to this problem is to adjust the position of the cameras so that the occlusion is minimized. Chen et al. mounted a wide-angle camera on a crane boom to track moving objects during the lift operation (Chen et al. 2017). They proposed a framework to detect and track the objects' locations in 3D by aligning the 2D image frames with the 3D site point cloud. The tracking and updating loops were executed asynchronously to enable real-time operation of the framework. The proposed method was successfully validated with a mobile crane in five different lift scenarios with different moving objects such as vehicles and workers (Fig. 10.7).

10.3.4 Task 4: Operation Analysis and Planning

As mentioned earlier, crane usually operates in very dynamic and complex environments where human operators struggle to comprehend the safety and efficiency situation and make timely decisions. In a CPS-ICS, once the physical status of the crane and the condition of the environment is captured through the sensor system, computer algorithms automatically analyze the safety and efficiency situation in operation and yield timely feedback such as providing warnings to potential risks and suggesting alternative lift paths. In this task, the key enabling technology is path planning and *safety hazard detection*.

Safety hazard detection refers to an automated process to identify crane-related safety hazards based on pre-defined safety rules. In crane lift operations, most common safety hazards include overloading, collision, and tip-over (Beavers et al. 2006). While overloading incidents can be effectively prevented by LMI systems, detecting the collision and tip-over risks mainly relies on the operator and the spotter's vigilance and judgement. In a CPS-ICS, collision hazards can be detected by a program that continuous monitor the clearances between crane parts (including the payload) to surrounding obstacles based on real-time sensor data. Such program can specify clearance thresholds for different types of collisions based on safety regulations or best practices. Furthermore, future movement patterns of relevant objects can be predicted based on their kinematics information (e.g., velocity, orientation, acceleration) derived from spatiotemporal sensor data, so that pro-active warnings can be returned to the operator. Tip-over risks can be detected by continuous monitoring the states of crane mechanical parts (e.g., hydraulic and outrigger systems) and setting boundaries for maneuver velocity and acceleration.

Lift path planning is a fundamental task in crane lift operations, aiming to plan a collision-free and efficient lift path based on anticipated payload properties (e.g., size, weight) and relevant site spatial constraints. Traditionally, the lift path is planned only for critical lift tasks (e.g., blind lifts, load weights more than 75% of crane lift capacity) and mainly depending on the planners' intuition and experience and this process is often labor intensive and error prone (Lei et al. 2013). Recently, researchers have adopted techniques in robotic motion planning to automate the lift planning process. In this approach, a crane is treated as a multi-degree-of-freedom robotic manipulator and thus searching algorithms can be applied to find a lift path in the crane's configuration space. There are three major concerns of lift path planning: efficiency, solution quality, and success rate. The existing methods used combinations of different search algorithms and collision detection strategies to fulfill the above-mentioned criteria. Algorithms that have been investigated for crane lift path planning include Heuristic Search (Soltani et al. 2002) (Sivakumar et al. 2003), Probabilistic Road Map (Chang et al. 2012), Rapidly Exploring Random Tree (RRT) (Kuffner and LaValle 2000) (Lin et al. 2013) (Zhang and Hammad 2012) (AlBahnassi and Hammad 2012), and Genetic Algorithm (GA) (Ali et al. 2005) (Cai et al. 2016). One example of computer-aided lift path planning is shown in Fig. 10.8. Theoretically, crane lift path planning is a rather simple robotics problem as cranes typically have a smaller number of degree of freedom, comparing to most manufacturing robots. However, this robotics problem becomes complicated as cranes operate in a much more dynamic and complex environment, as we discussed earlier. So far, lift path planning algorithms proposed in previous research were tested theoretically via computer simulation with rare implementation reported for practical uses. Therefore, finding an optimal as well as a practical solution for the crane lift path planning problem remains a challenging research topic.



(a) Path generated using the C-spaces trategy (b) Path generated using the online strategy (c) Path generated using the hybrid strategy

Fig. 10.8 Computer-aided planning for crane lift paths (Cai et al. 2016)

10.3.5 Task 5: Control Feedback

Section 2 introduced two control feedback modes: autonomous feedback and *human-in-the-loop feedback*. At the current stage, **autonomous feedback** is limited to emergent brake (Neitzel et al. 2001) and payload stabilization (Ren et al. 2015). Most maneuvering tasks still need to be performed by the human operator. This section discusses the human-in-the-loop feedback in regard to the design of an effective user interface.

A user interface (UI) is the main channel for the communication between the operator and the system. The information presented by the UI has to be concise and easily understandable so that the operator can perceive the information with a minimal cognitive workload. Traditional crane systems such as the Load Moment Indicator (LMI) provide the operator numerical feedback, with which the operator has to interpret the information based on his/her understanding of the current operating context (e.g., crane states and environment conditions). This manual interpretation may adversely increase the operator's cognitive load, offsetting the benefits provided by the crane system. Therefore, it is important to design an effective user interface (UI) that is able to provide the operator context-rich and most relevant information that is easy to comprehend. For example, Fang and Cho designed an interactive graphical user interface that visualizes crane states and the environment conditions in real-time (Fang and Cho 2016) (Fig. 10.9). The view angle of the main view was controlled by the operator's voice commands and the elevation view and the top view are useful to understand the elevation and position of crane load and parts. In addition to the three views, the UI delivers information including visual and auditory warnings for collision hazards and excess load sway, obstructions in proximity to the load or crane parts, and current lift path. Such visual information can be made accessible to other users (e.g., rigger, safety manager) on remote computers or mobile devices using a local or cloud-based server-client network. In addition to the content, the UI setup (e.g., screen size and position) can greatly affect the operator's perception of the content. In the development of a tower crane navigation system, Lee et al. assessed the usefulness of different screen sizes in visualizing

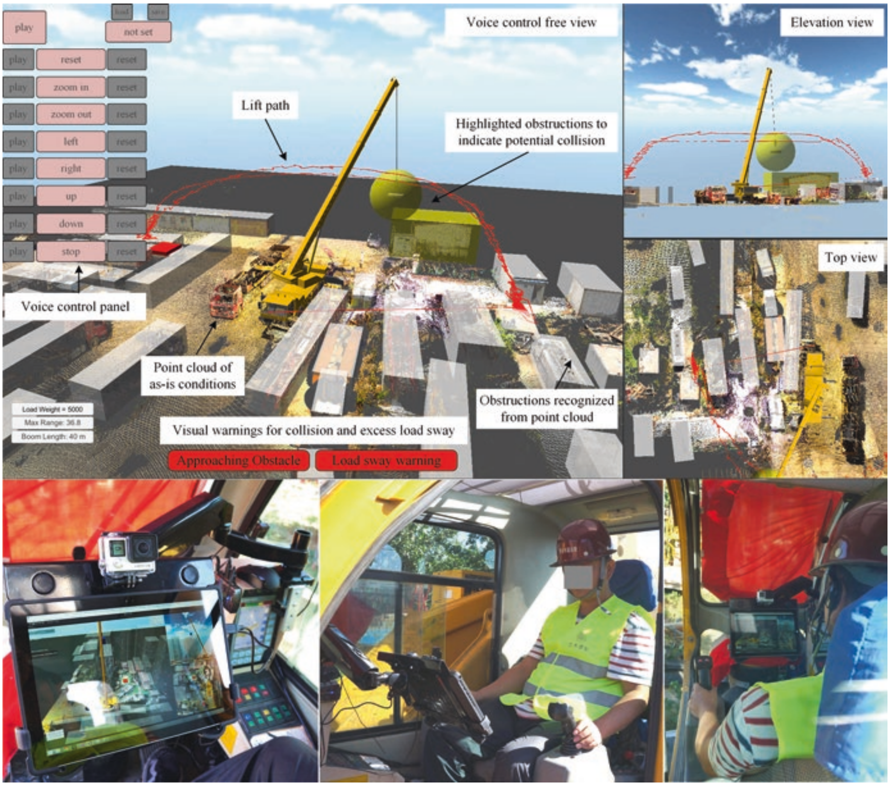


Fig. 10.9 A graphic user interface and its cabin setup in the human-in-the-loop feedback (Fang and Cho 2016)

real-time crane information (Lee et al. 2012a). Based on the feedback from operators, they determined that a 13-inch screen most effectively maximized the screen visibility in the confined space of a crane cabin.

In addition to these five major tasks, another very important technical component in CPS-ICS is ***Information and Communication Technology (ICT)*** that enables data and information transfer between all CPS entities and processes. The CPS-ICS can implement a rendezvous server to collect local sensor data, push data to a cloud server for processing and analysis, and retrieve and forward results to the user interface or the actuator system for action. Various off-the-shelf solutions are available for setting up a local communication network such as WiFi, Bluetooth, and Zigbee, depending on the requirements for transfer range and power consumption. For communication between a rendezvous server and the cloud server, the CPS may adopt a WiFi or line connection together with a cellular connection to make sure that the transient congestion over either connection will not affect the timely delivery of data. The communication protocol that manages the multi-access wireless spectrum between the sensors and the access points are also key to minimizing the latency.

10.4 Future Development of CPS-ICS

The global construction industry is undergoing a drastic evolution in digitalization and automation. In this trend, emerging technologies provide promising opportunities for the future development of CPS-ICS.

Artificial Intelligence (AI) Research and applications of Artificial Intelligence (AI) has gained remarkable attention in recent year, especially on autonomous vehicles, medical diagnosis, and natural language processing. Development of AI has multiple apparent benefits to CPS-ICS: the system can understand the scene better with more accurate recognition and prediction of object behaviors; path planning algorithms can yield more precise and robust results that may potentially eliminate the need of human intervention and achieve fully automated lift operations.

Augmented Reality (AR) Augmented Reality (AR) technologies have become more accessible and affordable with advances in both hardware and software. As an alternative to a physical screen, the virtual contents in the UI of the CPS-ICS can be presented to the operator via an AR-based head-mounted display (HMD) or head-up display (HUD). By overlaying the virtual content on physical objects or areas of interest, an AR-based UI allows the operator to perceive the virtual content in a more intuitive and contextual way (Chi et al. 2013). Despite the apparent benefits of AR, limitations in existing technologies such as low visibility in bright outdoor environments, limited field-of-view, motion sickness after long-time use need to be properly addressed (Steptoe et al. 2014).

Big Construction Data Handling The cloud server and the processing algorithms are expected to handle a large amount of heterogeneous construction data that are collected by numerous sensors at the worksites. The data also include the activities workflow, the asset inventories, as well as dynamic environmental conditions at the work sites. In a cloud-based system design, data storage is unlikely to be a problem. However, the requirement for real-time processing of big data in support of decision making is challenging.

10.5 Conclusions

Construction cranes, as the most important type of construction machinery, play a pivotal role in the efficient and safe execution of construction projects. This chapter introduced a high-level CPS framework for intelligent crane operations that consists of sensing, analysis, and feedback processes. Based on this framework, this chapter discussed four main tasks: crane state sensing; work environment modelling; mobile asset tracking; operation analysis and planning; and control feedback, together with multiple key enabling technologies including real-time location systems (RTLS), computer vision, laser scanning, rotary encoders, Building Information Modeling

(BIM), Structure from Motion (SfM), safety hazard detection, lift path planning, user interface (UI), and Information and Communication Technology (ICT). In addition, incremental improvements in the areas of Artificial Intelligence (AI), Augmented Reality (AR) and Big Construction Data Handling among other emerging technologies are expected to have huge impact on enhancing the intelligence in crane operation, possibly leading to fully autonomous crane operations, and machinery operations in general, in the near future.

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Chapter 11
CPS–Based System for Enhanced Mobile Crane Safety

Congwen Kan, Chimay J. Anumba, Yihai Fang, and John I. Messner

11.1 Introduction

Operating construction machinery represents one of the most dangerous tasks on construction sites. Often accidents related to machinery operations have significant safety and cost implications for the project. It was reported that collisions, struck-by accidents, and rollovers caused by various machinery account for one-quarter of the construction worker fatalities in the US (Hinze and Teizer 2011). Among commonly used equipment, cranes have a large share in accidents. As suggested by Neitzel et al. (2001), construction fatalities in which cranes are involved account for up to one-third of total fatalities. Crane operations are inherently hazardous due to the spatial constraints and the dynamic nature of construction operations. This point has been covered in the last chapter, but the importance of crane safety performance cannot be emphasized enough.

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As one of the most used types of cranes in construction projects, mobile cranes have very distinct uses. While tower cranes sit at a fixed location and operate within a given workspace, mobile cranes have more mobility and flexibility in performing the lifting tasks. It hoists and transports a variety of loads to its designated lifting position, often sharing the same workspace with workers and other machinery. While moving to its designated lifting position or performing the lifting tasks, crane operators hardly receive adequate information concerning the surrounding conditions and the object being lifted (Hinze and Teizer 2011). As for mobile cranes, the visibility is even more limited since the crane cabin in which the operator sits is attached to the crane base on the ground. The operator's visibility can be easily blocked by obstructions on site or the building under construction. This makes it very difficult for operators to be fully aware of the dynamic context and spatial constraints of the site environment, thereby resulting in potential safety hazards and operational inefficiencies. In this sense, broadening the bandwidth of communications to the operator is of critical importance.

With the aim of providing real-time safety assistance for mobile crane operations, this chapter presents a Cyber-Physical Systems (CPS)-based Intelligent Crane System (ICS). As has been defined in Chap. 10, an ICS is capable of capturing crane operation data, analyzing safety and efficiency conditions based on the data, and providing feedback to the crane operator for informed decisions. By building the system upon the concept of CPS, a CPS-based ICS (CPS-ICS) is expected to identify and mitigate potential mobile crane-related hazards in real-time or near real-time.

Building on Chap. 10, this chapter presents a detailed implementation of CPS for mobile crane operations. The remainder of this chapter is comprised of five sections, starting with a multi-layer system architecture. The workflow in building the system as well as the key enabling technologies required for CPS integration are outlined. This is followed by a presentation of the system development environment (including software and hardware requirements) for the CPS-ICS. Subsequent to this section is a presentation of the validation of the developed system on a full-scale construction site. In the concluding part of the chapter, challenges of the CPS-ICS are discussed, and suggestions are made on possible future research trajectories. A summary of this chapter is presented in Sect. 11.6.

11.2 System Architecture for CPS-ICS

Based on the high-level framework developed in the previous chapter, a multi-layer system architecture is developed to facilitate the implementation of the CPS-ICS, as shown in Fig. 11.1. The system architecture brings together the functionality and the key enabling technologies as a framework for bi-directional coordination between the cyber space and the physical world.

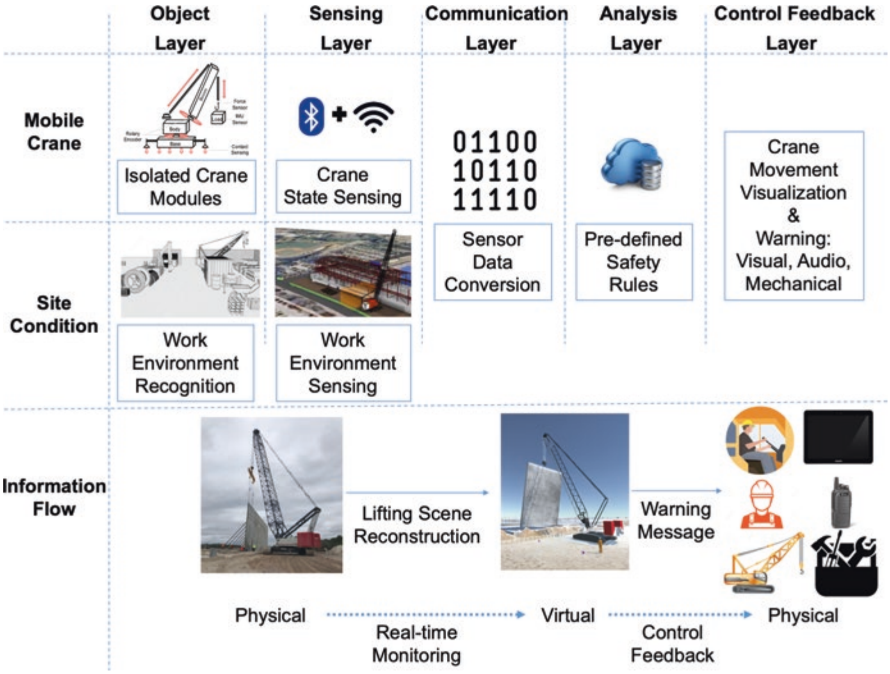


Fig. 11.1 System architecture for CPS-ICS

11.2.1 Object Layer

At this layer, mobile crane and the surrounding work environment are studied to develop an intuitive understanding of the dynamics on the physical site. The object layer consists of the physical mobile crane and the existing work environment. Different modules of a mobile crane and essential site components are identified so that their motion data can be obtained at a later stage.

Isolated Crane Modules Mobile crane comes in a great variety of types and configurations. However, it can generally be seen as an entity which comprises several rigid bodies connected by joints (Kan et al. 2018a). Based on its operating mechanism, a mobile crane can generally be decomposed into base, body, boom, and load, as shown in Fig. 11.2.

Work Environment Recognition The operator's situational awareness plays a key role in ensuring the safety of a mobile crane (Fang et al. 2018a). Maximizing the visibility and awareness of the operator requires the work environment to be perceived accurately. In this context, it is important to recognize the components that might interact with the mobile crane within the work environment. Generally, there are three types of components to be identified: (1) geological site environment, such as terrain and trees, (2) site layout including the location of essential site components such as jobsite trailer, material stacks, etc., and (3) the structure under construction.

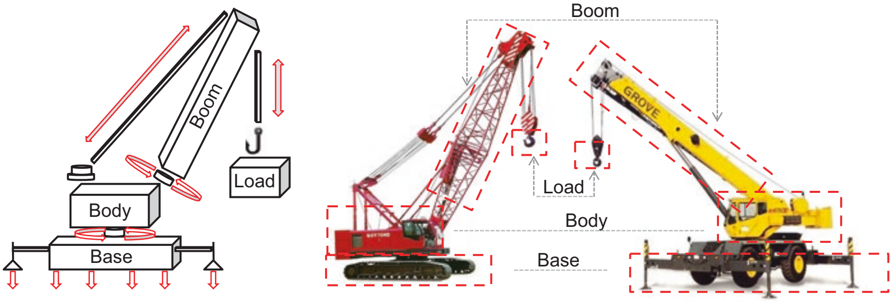


Fig. 11.2 Representation of isolated crane modules (Kan et al. 2018a)

11.2.2 Sensing Layer

In the sensing layer, the motion of the crane and critical components within the work environment, identified in the object layer, are captured through a sensing system incorporating different types of sensors. Sensors adopted for data acquisition are discussed in the next section.

Crane State Sensing Sensors are allocated on the afore-identified crane modules to capture the movement of each isolated module. Critical motion data to be obtained includes: (1) boom length, (2) boom slew angle, 3) boom lift angle, and 4) payload state.

Work Environment Sensing Information to be captured can be categorized into as-is site condition and dynamics on site. The as-is site condition refers to the allocation of the site components identified in the object layer. In addition to the as-is site condition, dynamics on the physical site, such as worker behavior and crane movement (as a whole entity), also need to be considered. A combined use of Building Information Modeling (BIM) and proximity sensing system are leveraged to model the as-is site condition and to reflect the changes.

11.2.3 Communication Layer

The communication layer serves as a data processing unit. This unit processes the crane motion data and work environment data collected by the sensing system and converts them into software readable packets. These software readable packets are labeled as processed data. The processed data will reconstruct the crane pose and work environment in a virtual platform, which is discussed in the Control Feedback Layer. Changes in the crane state and work environment are also reflected in this virtual platform in real-time.

11.2.4 Analysis Layer

Once crane motions and the updates within the work environment have been reconstructed, the processed data are transferred from the communication layer to the analysis layer to identify dangerous situations. Potential safety hazards and corresponding solutions are embedded in the virtual platform, which is centrally managed in this layer. A predefined system logic in dealing with dangerous situations is outlined in Fig. 11.3.

In order to identify potential hazards that may induce mobile crane-related accidents, accident records listed on the Occupational Safety and Health Administration (OSHA) website are studied. Based on the descriptions of the records, proximal causes of hazardous events were identified, as shown in Fig. 11.4. A series of thresholds extracted from OSHA citations are set to avoid potential hazards. Taking electrocution hazard, for example, it is regulated under citation 1926.1408(a)(2)(ii) that no part of the equipment, load or load line could get closer than 20 feet to the power line. In this case, 20 feet is used as the threshold for detecting electrocution hazard and is assigned to each part of the crane which is subject to the hazard. The clearance is defined as the closest distance between the surface point of each object in this study. When potential hazards are detected under an emergent condition, control feedbacks will be triggered respectively. Records of hazardous events are constantly logged to assist in further analysis.

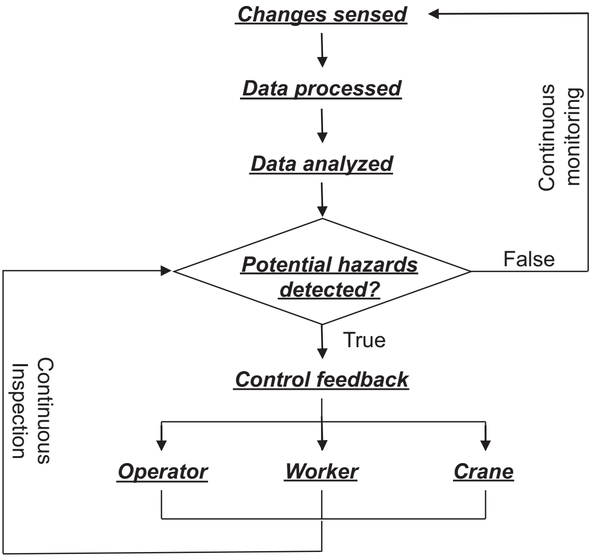


Fig. 11.3 Predefined system logic for potential hazards identification (Kan et al. 2018b)

Proximal Causes	Citations	Citation Number
Struck by	Work area control	Sec. 1926.1424
	Assembly or disassembly	Sec. 1926.1403-1926.1406
	Keeping clear of the load	Sec. 1926.1425
	Free fall/controlled load lowering	Sec. 1926.1426
Electrocution	Working near energized power lines	Sec. 1926.1407-1926.1411
Crane tip-over	Prevent from overloading	Section 1926.1417
	Outrigger/stabilizer use	Section 1926.1404(q)
Falls	Fall protection	Sec. 1926.1423
	Hoisting personnel	Section 1926.1431
Failure of crane	Proper assembly procedures	Sec. 1926.1403
	Safety devices	Sec. 1926.1415
	Operational aids	Sec. 1926.1416
	Inspection requirements	Sec. 1926.1412
	Wire rope inspection	Sec. 1926.1413
	Wire rope selection and installation criteria	Sec. 1926.1414

Fig. 11.4 Proximal Ccuses for mobile crane-related accidents & corresponding OSHA citations (Kan et al. 2018b)

11.2.5 Control Feedback Layer

Once potential hazards occur and are detected by the system, control feedbacks will be triggered and relevant information will be pushed to respective parties such as the crane operator, workers involved in the hazardous events, and the mobile crane itself. Control feedback to the crane refers to the automatic control implemented on the crane when a condition is diagnosed as dangerous. An example of automatic control is the use of a self-locking safety brake to prevent hoists from exceeding a predetermined operating speed or load limit.

In this study, the control feedback is designed to be delivered to the crane operator only, in the form of both visual and audio cues. The visual form provides enriched information including visualized data and prompt alerts to the operator through a mobile device mounted in the crane cabin. A user interface (UI) has been designed to display the reconstructed crane pose, surrounding work environment, along with any warning messages triggered accompanied by a warning sound.

11.3 System Development Environment for CPS-ICS

The system development environment involves both hardware and software environment for developing the CPS-ICS. The hardware environment provides the equipment required for system development or simulation. Examples include sensors for crane state sensing as well as work environment updating and mobile device for visualization. The software environment includes the communication network used for data transmission, and the software platform used for crane motion reconstruction and work environment modeling.

11.3.1 Crane State Sensing

The type of sensors adopted for mobile crane motion data acquisition is Inertial Measurement Units (IMU). An IMU is an electronic device assembled with a combination of accelerometer, gyroscope, and sometimes magnetometer (Dissanayake et al. 2001). It estimates orientation by combining the data it gets from the three embedded sensors: (1) a gyroscope which measures rotational rate, (2) an accelerometer which measures the linear acceleration, and (3) a magnetometer which measures magnetic direction, which is commonly used as a heading reference (Dissanayake et al. 2001).

Generally, an IMU has one accelerometer and one gyroscope for each of the three axes. When rigidly mounted to a point, the IMU measures the linear and angular acceleration and automatically calculates the orientation of the object attached to this point (Zhang et al. 2005). Given the measured angular orientation of each axis, an estimated position can be calculated by transforming the angular measurements to absolute positions (Fang and Cho 2015). With the ability to track position changes and report inertial measurements, IMU was chosen to capture the position of the crane boom and monitor the load sway. Two IMUs were proposed for installation at the tip of the boom and on the hook block, as shown in Fig. 11.5. The sensing system collects crane motion information including (1) boom slew angle, (2) boom lift angle, and (3) load sway.

It should be noted that the sensing system presented here was developed for a lattice boom crawler crane, but the uses are not limited to this specific crane type. The applications of the sensing system can be extended to other types of mobile cranes by using the same approach to break down the crane into modules as previously discussed.

In order to further validate IMU's ability in tracking the location of the boom and monitoring the load sway, two experiments were conducted and illustrated as follows.

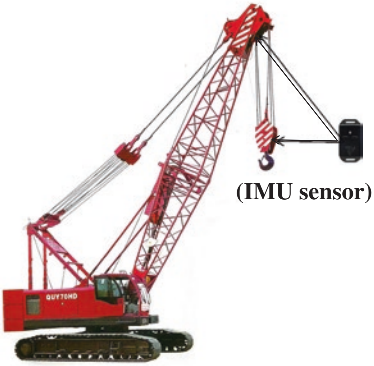


Fig. 11.5 IMUs deployment on a mobile crane

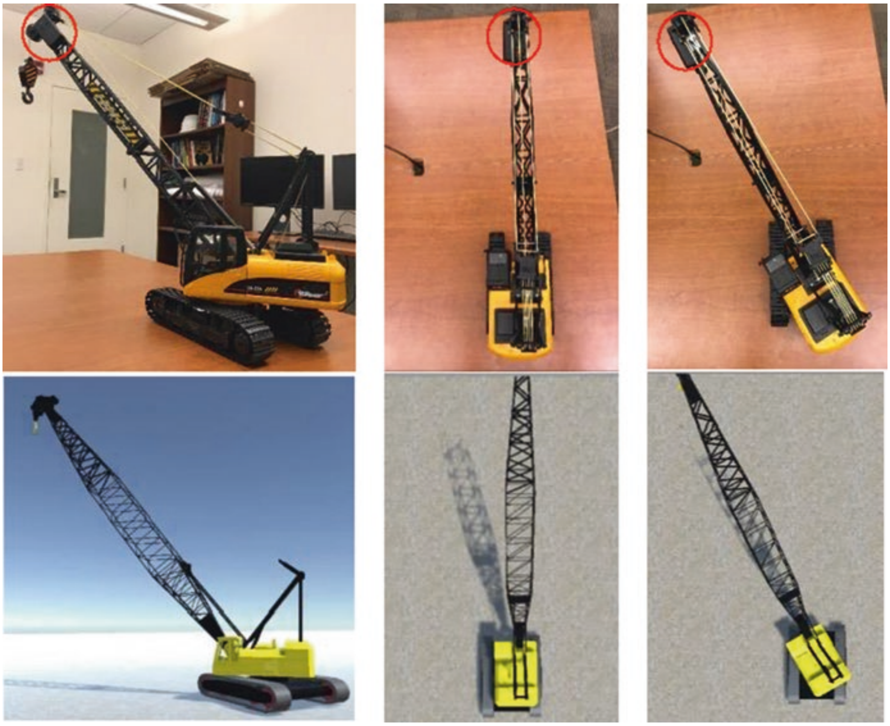


Fig. 11.6 Crane boom position reconstruction

Slew and Lift Angle A model mobile crane capable of emulating actual mobile crane movement was used in this experiment. An IMU was mounted on the tip of the crane boom to capture its movement, which was controlled by a remote controller. A cyber 'twin' mobile crane model was created in the virtual platform. Using the data captured by IMU, the crane boom position was successfully reconstructed in the virtual platform, as shown in Fig. 11.6. According to the time-stamped video capture, no noticeable latency was observed between the reaction of the cyber mobile crane and the movement of the physical crane model.

Load Sway In order to better simulate the condition of crane load sway, a tripod was equally spaced and firmly fixed on the ground to establish a stable leveled point. A round load with an IMU vertically attached was hung using a steel chain and securely mounted through the leveled point, as shown in Fig. 11.7. A communication dongle unit is needed in order to transmit the data to the central computer, as shown in Fig. 11.8. The data received by the computer are constantly written to a .txt file for further analysis.

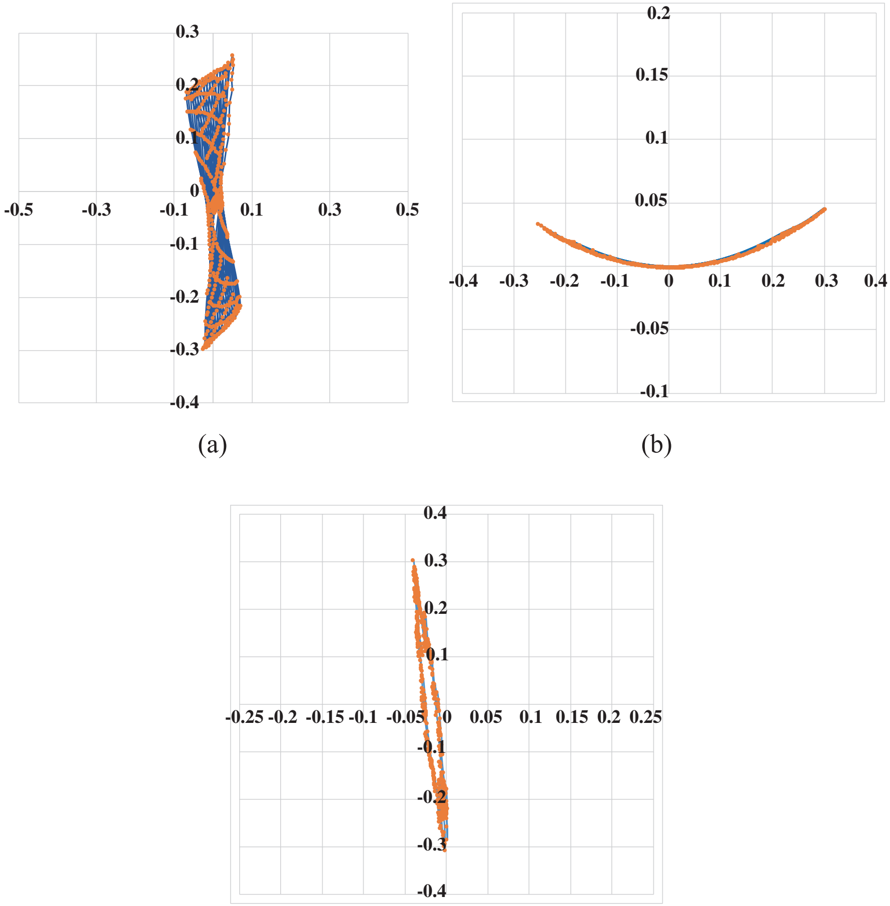
In order to test the performance of IMU in monitoring crane load sway, the following scenario was designed to simulate a 'sway' condition. The load hosting the IMU sensor was lifted 0.3 meters off its original resting position with the steel chain fully stretched and was released with a lateral force. Consequently, the load started

Fig. 11.7 Load sway simulation

Fig. 11.8 Central computer setup

to sway annularly. A total of 973 measurements were captured by the IMU in approximately 60 seconds, and then the load was stopped manually. The measurements recorded in the .txt file were exported into Excel for analysis. A data conversion algorithm was applied and load sway trajectory was simulated. The results are shown in Fig. 11.9 (a), (b) and (c) are for XY, YZ and XZ plane respectively, with the dots denoting the exact measurements and lines mapping out the trajectory. It should be noted that the units are in meters.

As the results indicate, the load sway is an evenly-displaced oval shape, which matches what was observed during the experiment. In this regard, the IMU is capable of accurately tracking the load sway. In addition, the successful reconstruction of boom and load positions also indicates that the algorithm for transforming angular measurements to absolute positions works as expected. Thus, the proposed use of IMUs for tracking crane boom position and load sway is validated and can be further carried out on the site for a full-scale validation.



(a) (b)

(c)

Fig. 11.9 (**a**) Sway trajectory in XY plane (**b**) sway trajectory in YZ plane (**c**) sway trajectory in XZ plane

11.3.2 Work Environment Updating

In addition to sensing crane state, another major task for safety consideration is to keep track of the mobile assets which might interact with the crane within the work environment. To do that, iBeacon, a Bluetooth-based proximity sensing system is adopted. The system consists of two parts: Bluetooth signal transmitter (iBeacon) and crane operator's receiver (mobile device mounted in the crane cabin). The iBeacons are able to constantly broadcast their signal to the Bluetooth-enabled mobile device. Based on the strength of the signal, the approximate distance between the iBeacons and the mobile device can be determined. This iBeacon-based proximity sensing system is leveraged to monitor the distances between the mobile assets and the crane so as to create a hazard detection area around the crane. In order to test if

Table 11.1 Collision warning system

Collision probability	Safety threshold	Warning message triggered
Moderate	20 feet	Danger detected: decelerate
High	10 feet	Danger detected: decelerate immediately
Severe	5 feet	Critical situation: stop immediately

potential collision hazards can be effectively detected, a three-level collision warning system was created, as shown in Table 11.1. Three thresholds representing different degrees of dangerousness were set to gauge the system capability in measuring distance. Corresponding warning messages would be initiated and displayed to the crane operator through the mobile device upon assets tagged with iBeacons breaching the safety thresholds.

When creating a hazard detection area around the crane, it should be noted that crane is a giant entity whose size is not negligible. While mobile assets such as workers can be treated as a rigid body with fix dimensions represented by iBeacon, a mobile crane certainly cannot be represented by the mobile device mounted in the cabin. To solve this, a crane-shape buffer area is added to the crane model in the virtual platform to take account of the dimension of the crane. In this regard, in addition to tracking the distances between mobile assets and the tablet, the system is able to track the distances between mobile assets and any part of the crane.

Apart from tracking mobile assets on site, the crane's location should also be tracked while it moves as a whole entity. This can be achieved through the use of iBeacon as well. Three reference iBeacons are to be set to three stationary points with known coordinates. By computing an algorithm named triangulation, the crane's approximate location (represented by the mobile device with the buffer area added) can be determined based on the distances between the mobile device and the three reference iBeacons. This method was tested in a 16 × 16 ft. room. As shown in Fig. 11.10, three iBeacons were placed on three sides of the room, while the mobile device was placed in the middle of the room. The triangulation algorithm has been embedded into the virtual platform, with the location of the reference iBeacons set based on their real-world location, as shown in Fig. 11.11. The three numbers displayed on the top left corner of Fig. 11.11 indicate the distances between the mobile device and the three reference iBeacons. These numbers are calculated averages excluding outliers. By 'triangulating' these three numbers, the location of the mobile device can be pinpointed, represented as the intersection of the three circles. Figure 11.11 shows the real-time tracking result of the set-up shown in Fig. 11.10.

This test scenario gave out very sensitive results--the distances between the iBeacons and the mobile device (the three readings in Fig. 11.11) are not stable. There are quite a few conditions that could affect accuracy. Firstly, Bluetooth signal transmission highly depends on the transmission power settings as well as environmental factors. It can suffer interference, be diffracted or absorbed. The presented case is an ideal scenario that does not account for reflections and interference. In addition, iBeacons have to have Line of Sight (LoS) to provide accurate ranging results. Presence of obstructions that could block LoS would result in reflected signals

Fig. 11.10 Triangulation test room setting

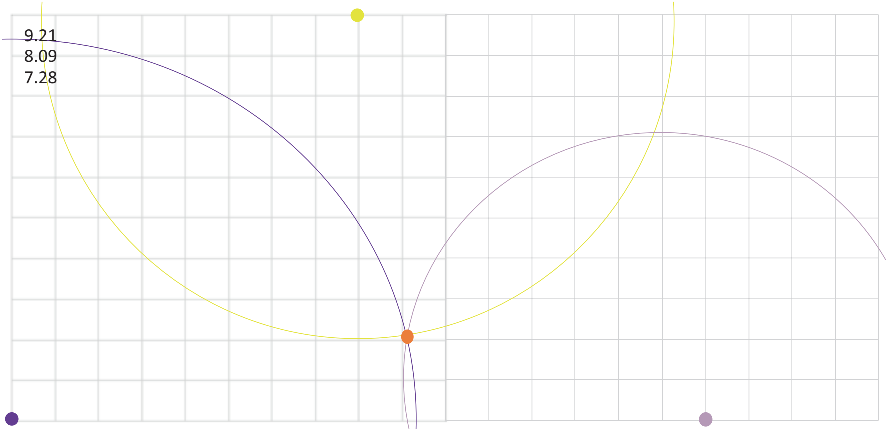


Fig. 11.11 Visualized result of triangulation

reaching the mobile device and inconsistent ranging results. In this sense, further tests were carried out on site where signal reflection can be reduced and LoS is improved.

11.3.3 Virtual Platform Development

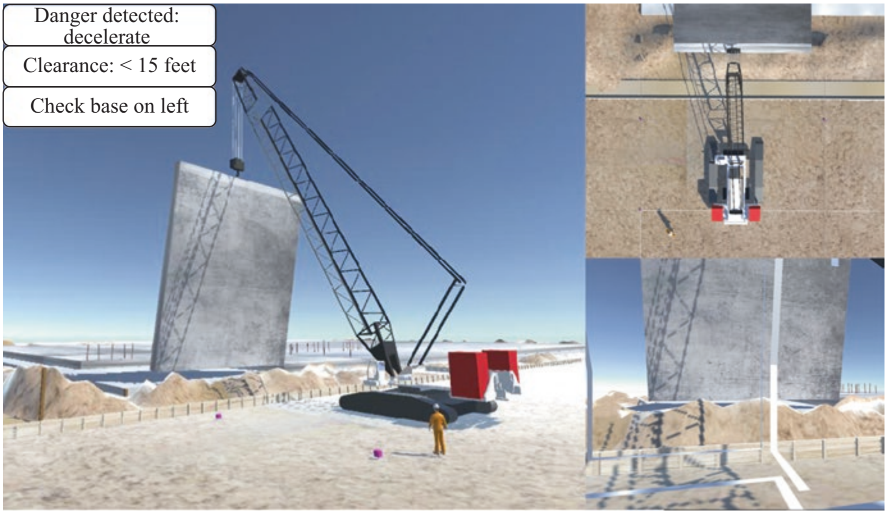
Unity 3D was selected as the software environment for virtual platform development. It was selected in this study for its ability to support cross-platform scripting, 3D modeling, and visualization. Other platforms with similar capability would also be practical.

Crane Modeling The first step in building the virtual platform is to create the mobile crane model. A 3D model of a mobile crane was downloaded, broken down into parts, and imported into Unity 3D. Scripts were added to each part of the crane model (e.g., base, body, boom and load) to allow them to move freely in the virtual platform as they do in the physical world. The motion of the crane model was built to be manipulated through keyboard control initially and later to be updated through the data collected by IMUs. The safety rules together with the corresponding predetermined thresholds are also embedded with the crane model or part of the model to account for different types of potential hazards.

Work Environment Modeling A 3D BIM model incorporating all essential site components within the crane workspace was created. This baseline construction site model reflecting as-is site condition was assembled in Unity3D.

Mobile Asset Tracking Potential mobile assets such as workers were tagged in the virtual site model. The locations of the tagged items were to be updated through the data collected by iBeacons. Three control points were set in the virtual site model representing the three stationary iBeacons. Crane's initial location can be determined through triangulation with the three stationary iBeacons.

User Interface (UI) UI is the major form of communication between the crane operator and the system. It is important that the UI presents information and instruction clearly and concisely. As shown in Fig. 11.12, the UI developed consists of three views: an isometric view is shown on the left, a plan view on the top right and an operator's view on the bottom right. It was designed to present the operator with sufficient visualization of the reconstructed lifting scene along with any warnings triggered in real-time. The detection of a collision hazard is shown here as an



Danger detected: decelerate

Clearance: < 15 feet

Check base on left

Fig. 11.12 User interface shown on the mobile device example. Instructions regarding this hazardous situation, such as the designed safety clearance, detected clearance, and the questionable part of the crane, are displayed on the top left corner of the screen.

11.3.4 Mobile Device for Visualization

A mobile device refers to a portable computing device that has a screen for displaying information. An example of such a mobile device adopted in this study is a Bluetooth enabled tablet PC. The tablet is intended to be installed in the crane cabin to provide the operator with real-time mobile crane operational conditions, surrounding site conditions, and any supplementary information such as warning messages triggered. The use of a mobile device is not restricted to tablet only. Workers on site can also be equipped with portable mobile devices such as smartphones and smartwatches. Sound and vibration alerts can be provided upon breaching the predefined hazardous area around the mobile crane.

11.3.5 Communication Network

The communication network enables communication and coordination between the virtual platform and the physical mobile crane on site by enabling sensory data exchange. The communication network adopted in this study includes the Internet and wireless fidelity (Wi-Fi) for IMU data transmission and Bluetooth for iBeacon data transmission. With the sensory data transferred wirelessly through the communication network to the virtual platform displayed on the mobile device, the operational conditions of the mobile crane can be reconstructed and visualized by the operator in real-time.

11.4 Demonstration and Validation

To demonstrate and validate the proposed CPS-ICS, the operation of a 300-ton Link-Belt 348 crawler crane was explored. The crane was in use on a low-rise tilt-up construction project in Florida, US. An initial site visit was conducted prior to implementing the system on-site. Critical information concerning the site conditions and the crane configurations were obtained. Figure 11.13 (a) shows one of the critical lifts developed with 3D Lift Plan with all exact measurements plotted to reflect actual lifting conditions, which is shown in Fig. 11.13 (b). The crane model pre-developed in the virtual platform was modified based on the exact configurations of the crane being used.

The following sub-sections demonstrate the implementation of the system based on the major tasks identified in Chap. 10.

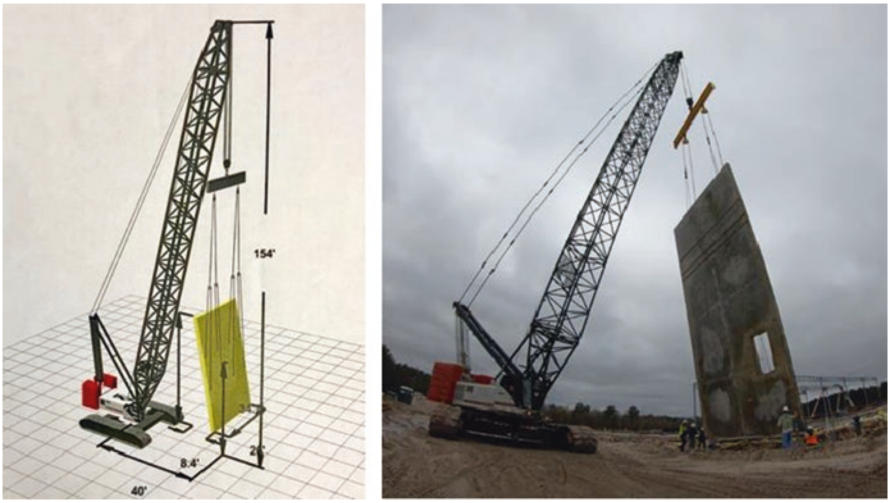


Fig. 11.13 (**a**) Critical lift developed in 3D lift plan (left) and (**b**) Real world condition (right)

Fig. 11.14 IMU Deployment

11.4.1 Task 1 Crane State Sensing

The sensing system adopted two IMUs to measure three critical motions: boom slew angle, boom lift angle and load sway. The two IMUs were attached to the tip of the boom and the hook block using a zip tie, as shown in Fig. 11.14. Both the slew angle and lift angle can be measured by the IMU attached to the tip of the boom, and the load sway can be captured by the IMU on the hook block.

It should be noted that the current orientation measurement does not match the origin since the surface where the IMUs were placed was not leveled. Therefore, when estimating the trajectory of the boom and the load sway, a deviation from the origin can be expected. In order to minimize this error, the two IMUs were calibrated before installation based on their resting pose on the two locations indicated in Fig. 11.14. Thus, the initial orientation is taken into consideration.

11.4.2 Task 2 Work Environment Modeling

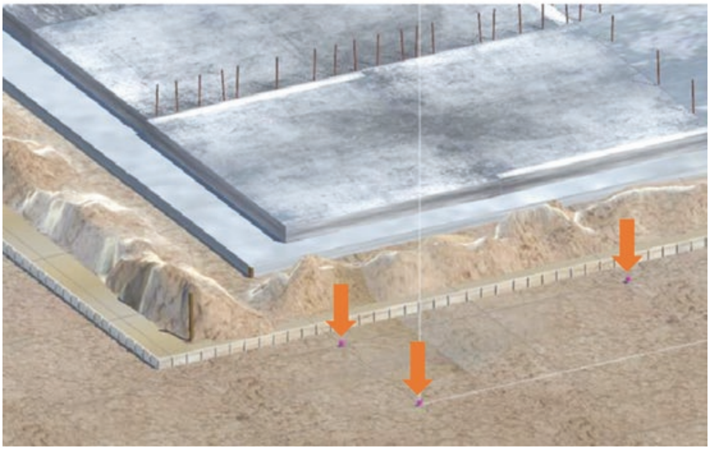
The modeling of the as-is site condition was completed prior to the on-site implementation. While emerging technologies provide a variety of choices for capturing as-is site conditions, a simple BIM model was used in this case due to the simplicity of the site conditions. As shown in Fig. 11.15 (a), tilt-up panels poured on the job site were resting on top of the slab-on-grade, waiting to be raised into a position to form the exterior walls. The mobile crane would move around the building's perimeter to lift the panels into place. The site is quite spacious so hardly anything can be found on the crane's moving path. Fig. 11.15 (b) shows the as-is site model created based on the information obtained from the initial site visit, such as the building footprint and size of each tilt-up panel.

11.4.3 Task 3 Mobile Asset Tracking

The leveled aspect of tracking mobile assets with respect to the crane is to initialize crane's position in the virtual site model. To do this, three iBeacons were deployed at the southwest corner of the building, where the crane started performing the lifting work. To reduce the multipath effect and achieve the best data transmission quality, the three iBeacons were placed approximately at the same level, and they were in view of each other without any obstacles in-between. In the virtual site model, coordinates of the three control points were adjusted based on the placement of the three stationary iBeacons on-site, as indicated in Fig. 11.15 (b). During the experiment, the mobile device carried in the crane cabin was able to receive the signal transmitted by the iBeacons and plot the movement of the crane. The movement data was also captured and written into a .txt file for further analysis.

After the successful initialization of the crane position, the three-level hazard detection area was tested. Workers holding iBeacon were instructed to approach the crane at a different angle. They were asked to stop at the three thresholds, 5 feet, 10 feet, and 15 feet respectively, to see if their existence can be detected and if the warning messages can be triggered correctly. This was conducted while the crane was not in operation due to safety considerations.

(a)



(b)

Fig. 11.15 (**a**) Real site condition (top) and (**b**) Virtual site model (bottom)

11.4.4 Task 4 Operation Analysis and Planning

While the main purpose of this task is to gauge the capability of the system in providing real-time safety assistance and improving lifting efficiency, this validation focused solely on the safety aspect, more specifically, the collision hazards. The first step in detecting collision hazard would be to precisely sense the crane state and reconstruct it in the virtual platform. This reconstructed crane model would also serve as the basis for detecting other potential safety issues associated with the crane. By integrating extra instrumentations or other technologies into the existing sensing system, the developed ICS would have extended capabilities in dealing with hazardous situations thoroughly.

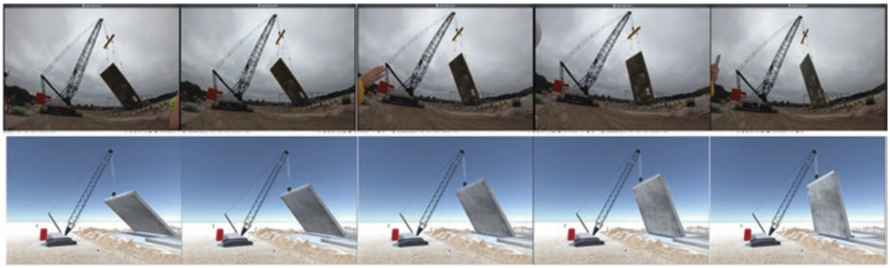


Fig. 11.16 Crane operations on site (top) vs. reconstructed crane operations in virtual model (bottom)

The results of crane motion reconstruction were validated by comparing the reconstrued virtual crane model to the time-stamped video captured on site using a camera. The top portion of Fig. 11.16 shows the screenshots of the actual lifting captured from the video, while the bottom portion shows concurrent reconstructed crane lifting scenes captured from the recordings of the virtual platform.

11.4.5 Task 5 Control Feedback

Control feedback was conveyed to the operator in visual and audio form through the tablet mounted in the cabin, as shown in Fig. 11.17. The user interface presented the operator with the reconstructed lifting scene comprises of the crane motion and the surrounding environment. The main isometric view on the left can be controlled through the touch screen (zoom in/out, rotate), so that the operator can easily find the focus of interest. The plan view helps the operator to conceive where the crane is with respect to other site components, while the operator's view on the bottom right offers a way to cross-check if the reconstructed lifting scene matches the actual conditions. In addition to the visualized lifting scene, information concerning potential hazards identified was also provided in the UI, accompanying with warning beeps.

11.5 Discussion and Future Direction

Based on the above exploration of CPS-ICS in dealing with the mobile crane safety issue, it is evident that CPS offers the potential for advanced control and management of mobile cranes on construction sites. While the proposed method has provided the solution to closely integrate the virtual model and the physical components of mobile crane operations, more applications and extensive benefits can be gained based on it. Possible future trajectories for this research include:

Fig. 11.17 Tablet deployed in the crane cabin for lifting scene visualization and potential hazard identification

Site Condition Updating Method Advancement Mobile cranes share the workspace with workers and other machinery. Recognizing the surrounding work environment is of equal importance to sensing crane state. The sensing system developed for site condition updating in this study was only able to track the mobile assets whose size is negligible, its ability to track changes on site comprehensively is limited. There is the need to adapt the site condition updating method to cope with the practical constraints of a complex construction site. Current methods in site components detection and tracking, such as real-time location systems (RTLS) and computer vision-based approach still have certain limitations in acquiring and processing data continuously in a real-time manner (Fang, et al. 2018b). Recognizing and updating site conditions in real-time is a very challenging task yet offers great potential in understanding the synergetic crane working environment thus to offer further safety improvements.

Big Data-Assisted Knowledge-Rich CPS-ICS During the development of CPS-ICS, all the information concerning mobile crane performance, site condition changes, together with the system instructions under various conditions are recorded in the database. The management and analytics on the vast amount of digital data generated have become a significant issue in the CPS context, and the need for using big data as an analysis method to support efficient data elaboration is well understood. Big data will be able to contribute to the CPS-ICS as it enables the direct analysis of theoretical values, historical data and the real condition of a project. Problems occurred previously can be learned, predictions can be made based on the pattern, and suggestions can be provided to avoid similar problems in the future.

Autonomous Control Feedback to the Crane Currently, the control feedbacks are only designed to be delivered to the crane operator. However, it takes time for human decision-makers to process the information and response to the condition. And this lag would cause issues in some critical situations. A comprehensive application of CPS enables the use of actuators to be leveraged on a mobile crane. The actuators would provide automatic control for immediate safety adjustments based on the system commands without human interactions. Although a degree of autonomy can be achieved by using actuators (which have been proved feasible in some other disciplines), they may induce unforeseen situations which may impair the safety of the workers or the stability of the crane. Therefore, further analysis is needed to take account of the effects induced by the autonomous control.

Enhanced Communication and Coordination Between Multiple Parties Recent advancement in information technology, such as cloud computing offers great opportunities in making the CPS-ICS more accessible. Visualization and control feedback results can be pushed to a cloud server for relevant team members such as crane manufacturers, project managers, supervisors/foreman to view on demand. It provides better opportunities for problem analysis, hazard avoidance, and collaborative working.

11.6 Summary

This chapter presented a detailed implementation of CPS-ICS for mobile crane operations. A system architecture was developed and the detailed workflow in building the system for CPS integration was discussed. The developed CPS-ICS was validated on a full-scale construction site to demonstrate its practical functionality. With the capability of enhancing bi-directional coordination between the physical conditions and their virtual representations, the CPS-based system offers advantages in effective planning, pro-actively monitoring crane operations, providing rich control feedback to the crane operator, and in turn, ultimately reducing or avoiding mobile crane-related accidents. Moving forward, extensive applications and benefits can be achieved by adding some of the emerging technologies to the existing system, such as cloud computing and big data.

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Chapter 12
Structural-Infrastructure Health Monitoring

Seongwoon Jeong, Rui Hou, Jerome P. Lynch, and Kincho H. Law

12.1 Introduction

Restoring urban infrastructure is one of the major grand challenges in the United States for the twenty-first century, as reported by the National Academy of Engineers (NAE) [NAE (2007)]. Bridges are of particular concerns as more than 50% of the bridges are now approaching 50 years or older [AASHTO (2008); FHWA (2008)]. As volume of vehicles crossing bridges continues to increase, signs of distress have begun to show on many of the bridges because of structural deterioration due to the increasing traffic loads. As reported by the American Society of Civil Engineers in 2017, over 9% of bridges are structural deficient and "$123 billion investment is needed to rehabilitate current bridge conditions" [ASCE (2017)]. New paradigms to structural asset management, that take advantage of modern technologies for maintenance and operations, are direly needed to enhance durability and to ensure operational safety of our aging infrastructure systems.

Traditionally, the primary operation and maintenance strategy employed for bridges has been the use of visual inspections (VI) [Rolander et al. (2001)]. However, VI has been shown to be a subjective process that relies mainly on the interpretation of the inspector, leading to significant variability in ratings [Moore et al. (2001)].

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VI can often identify issues observable from the surface; however, subsurface damage can be extremely difficult to identify. The limitations of VI has prompted the use of sensing technology. Permanent structural health monitoring (SHM) systems can be installed to measure bridge responses to traffic and environmental loads [Adams (2007); Farrar and Worden (2007); Moon et al. (2009)]. Indeed, there has been an increasing interest in deploying sensors and structural health monitoring systems for bridge rehabitation as well as for new bridge structures (for example, see [Kitching (2018)]). Instrumented with hundreds or thousands of sensors, the amount of data collected by a SHM system can easily reach gigabytes per day that need to be properly stored, managed and, more importantly, utilized.

Leveraging recent advances in wireless sensor networks and cyberinfrastructure tools, this chapter describes a research effort on developing a practical and scalable cyber physical system (CPS) framework for the monitoring of civil infrastructures. Specifically, the framework is designed to observe and measure the dynamic interactions between the bridge structures along a highway corridor (the stationary physical system) and traffic loads due to heavy trucks (the mobile agents). Even though heavy trucks are the greatest contributor to long-term bridge deterioration [Barker and Puckett (2007)], their load is difficult to measure using traditional sensors and monitoring systems. Without a measure of the load, deep understanding of the causal relationship between truck loads and deterioration remains murky, since structural health monitoring and damage detection algorithms that only use bridge response data have had limited effectiveness [Sohn et al. (2004)]. Furthermore, this application is especially challenging due to the highly transient nature of the interaction (e.g., interaction only occurs when the truck is crossing the bridge) which provides a highly compressed timeframe over which interactions can be observed, measured and controlled.

This chapter provides an overview on the prototype design and implementation of a CPS for bridge monitoring on a highway corridor at the State of Michigan in the US. The chapter is organized as follows: Section 12.2 provides an overview of the CPS framework for bridge monitoring. Instrumentation of the SHM systems on the bridges and the monitoring apparatus along the highway corridor are described in Sect. 12.2.1. A cloud-based cyberinfrastructure framework for data management and web services is discussed in Sect. 12.2.2. Selected application examples are presented in Sect. 12.3 to illustrate the utilization of the CPS for bridge monitoring. The chapter is concluded with a brief discussion on current and future works in Sect. 12.4.

12.2 A Cyber Physical System for Bridge Health Monitoring

The schematic architecture of a cyber physical system (CPS) for bridge health monitoring is shown in Fig. 12.1. Besides the physical system of the infrastructure system that consists of the highway bridges and passing vehicles, two additional cyberinfrastructure components are included in the CPS architecture:

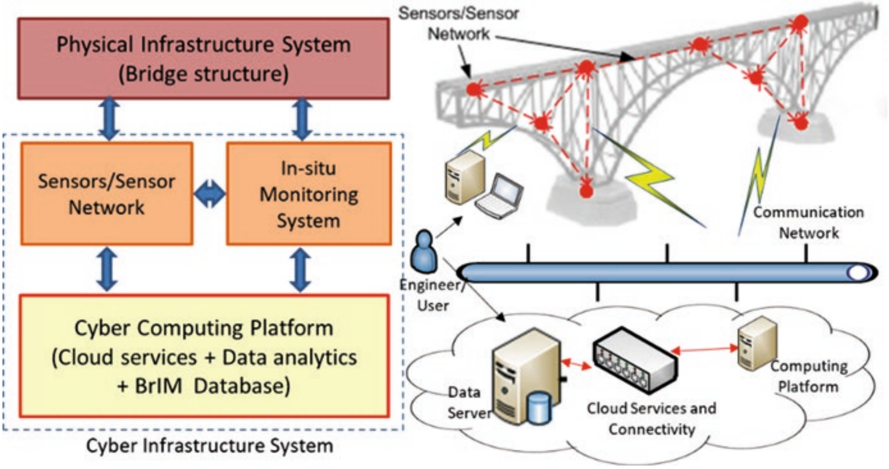


Fig. 12.1 Schematic of a cyber physical system for bridge health monitoring

1. The sensing and monitoring component, which includes the bridge SHM systems that monitor bridge responses to traffic, weigh-in-motion (WIM) stations that measure the speed, gross weight and weight distributions of vehicles, and traffic cameras that capture video images of the passing vehicles in the highway corridor; and
2. A cloud-based computing platform, that includes a database system for persistent storage of the data collected from the SHM systems and a repository of tools that support the application services for performance assessment of the monitored physical structures.

The following describe the design and implementation of these two cyberinfrastructure components.

12.2.1 Sensing and Monitoring of the Infrastructure System

As shown in Fig. 12.2, the testbed for the CPS system is a 15-mile highway corridor that includes two bridges instrumented with SHM systems for measuring structural responses, one WIM station for measuring vehicle loads and four traffic cameras to capture passing vehicles along the corridor.

Bridge SHM systems are implemented to monitor the structural responses of two highway bridges, namely the Telegraph Road Bridge (TRB) and the Newburg Road Bridge (NRB), carrying traffic along the highway. SHM systems were installed on the TRB and the NRB in 2011and 2016, respectively, using wireless sensors as the main data acquisition platform. The comprehensive wireless structural monitoring systems was designed and instrumented based on the Narada wireless sensor system

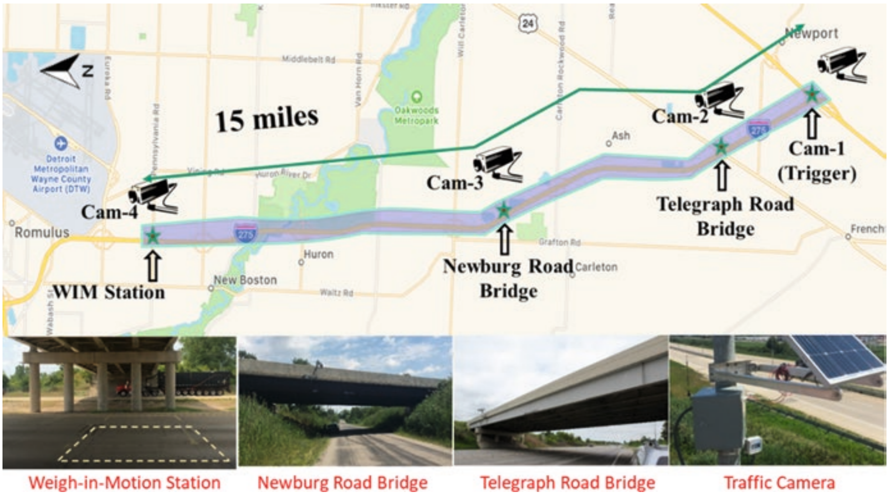


Fig. 12.2 A highway corridor for bridge monitoring testbed

developed at the University of Michigan [Swartz et al. (2005); O'Connor et al. (2017)]. A single board Linux-based computer serves as the base station that can send commands to and collect data from the Narada sensor nodes. Furthermore, the base station is responsible for forwarding the sensor data to the cloud and accessing services from the cloud server via a cellular network [Jeong and Law (2018)]. For the Narada wireless sensing nodes, each consists of an IEEE 802.15.4 transceivers for wireless communication between the sensor node and the base station. The base station and the wireless sensor nodes are solar powered.

Our discussion will primarily focus on the data collected by the SHM system installed on the TRB. Figure 12.3 shows the sensor layout of the TRB system. TRB is a deck-on-steel girder bridge with reinforced concrete deck that carries three lanes of traffic on seven steel girders. The bridge spans a total of 224 feet consisting of a main span of 128 feet and two abutment spans of 48 feet each. To measure the structural responses, the bridge is instrumented with strain gages and transducers, accelerometers and thermistors. As shown, a total of 15 accelerometers are installed to the bottom flange of the girders to measure vibration along Girder 1 and Girder 7 at the main span and at the center of the bridge. Six locations are instrumented for strain measurements, where, at each location, a strain transducer is installed in the slab and three strain gauges are installed along the depth of the girder. Each location also has one thermistor to measure temperature. A similar SHM system has also been installed on the NRB.

The cyber monitoring system takes advantage of a weigh-in-motion (WIM) station managed by the Michigan of Transportation (MDOT). As shown in Fig. 12.2, the WIM station is built into the road pavement of the two right lanes of the highway so that vehicle loads can be measured without slowing the traffic. The WIM station is capable of recording the load of each passing vehicle, including the arrival time,

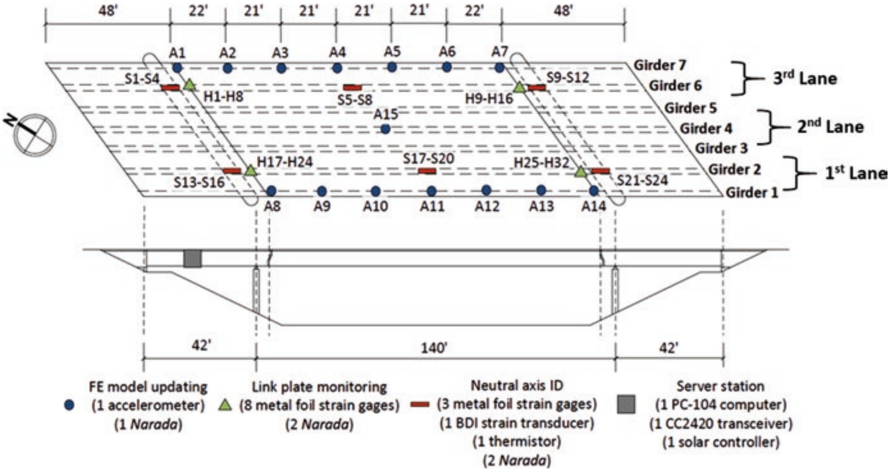


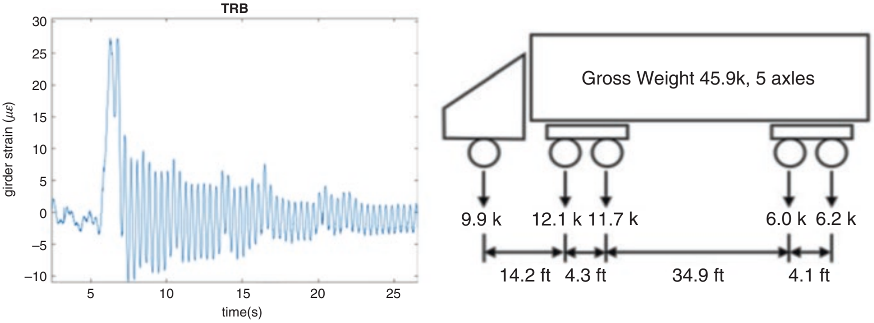
Fig. 12.3 Sensor layout on the telegraph road bridge

vehicle speed, vehicle gross weight, number of axles, axle weights, vehicle traveling lane and direction, and other information. The measurements are communicated via a fiber optic network to a data server managed by MDOT and made available for the study.

In addition to the sensors for measuring structural responses and the WIM station for capturing passing vehicles, four video cameras are installed along the highway. As shown in Fig. 12.2, a camera (Cam-1) is installed to capture vehicles as they enter the highway corridor. Cameras are installed on the TRB and the NRB to track the arrival and the movement of the vehicles on the bridges. One other camera is installed at the WIM station to capture the load profile of the vehicles. Each camera is controlled by a single board Linux server and is set to capture images at a frame rate of 10 frames per second (FPS). Each camera is connected to a GPU-enabled single board computer for real-time communication and on-board data processing. Each camera station collects and stores image data locally, and transmits the images to a central server using a cellular LTE modem.

One salient feature of the cyber infrastructure monitoring system is its triggering mechanism to record the vehicle loads and to link the traffic loads to measured bridge responses induced by the vehicles. In addition to a fixed routine schedule of measuring the structural responses every two hours for a duration of 10 min, the triggering mechanism enables data collection when a specific loading event of interest occurs. In this study, we are particularly interested in capturing the response of the bridges due to heavy trucks. Figure 12.4 shows an example of the truck load measurements by the WIM station and the corresponding strain measurements when the same truck crosses the two bridges.

Camera 1 **Camera 2 (TRB)** **Camera 4 (WIMS)**

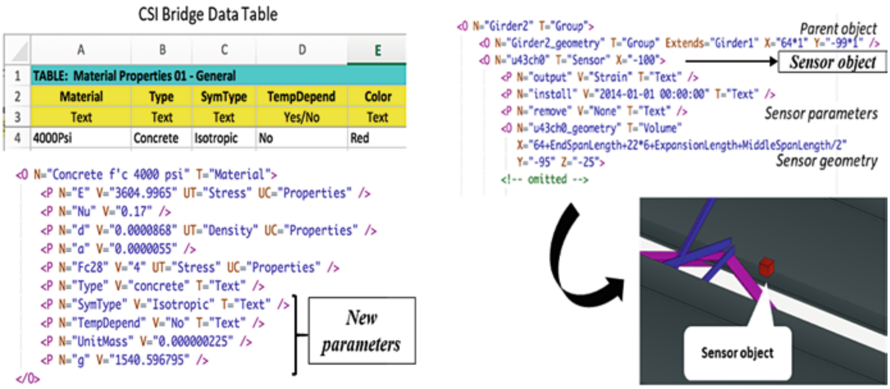


Strain Measurements due to Truck **WIM Measurements of Passing Truck**

Fig. 12.4 Capturing vehicle loads on bridge via video camera systems

12.2.2 A Cloud-Based Computing Platform

Bridge monitoring data comes from a variety of sources, including computer-aided design (CAD) systems, bridge management systems (BMS), structural health monitoring (SHM) systems, and engineering modeling and analysis tools. In current practice, these tools are isolated from each other and sharing of information across systems is limited. One of the objectives of the CPS is to build a scalable and flexible cyberinfrastructure framework that can handle and integrate the data originating from the diverse sources, as well as support and facilitate the development of SHM application services. The development of the cyberinfrastructure framework involves three basic tasks: information modeling, database management and cloud computing services. The information modeling task serves to develop a semantic representation of the system, including the description of the physical structure as well as the sensor information. A database system is designed and implemented on cloud servers as a persistent data storage media to manage the data. Standard web application programming interfaces (APIs) are developed and hosted on the cloud server to enable platform-neutral remote access to the database. With the API, the framework allows access to the data from external applications, such as engineering analysis and data analysis software tools, to support bridge monitoring activities.



CSI Bridge Data Table

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2	Material	Type	SymType	TempDepend	Color
3	Text	Text	Text	Yes/No	Text
4	4000Psi	Concrete	Isotropic	No	Red

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    <P N="Nu" V="0.17" />
    <P N="d" V="0.0000868" UT="Density" UC="Properties" />
    <P N="a" V="0.0000055" />
    <P N="Fc28" V="4" UT="Stress" UC="Properties" />
    <P N="Type" V="concrete" T="Text" />
    <P N="SymType" V="Isotropic" T="Text" />
    <P N="TempDepend" V="No" T="Text" />
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    <P N="g" V="1540.596795" />
</O>
```

```
<O N="Girder2" T="Group">
    <O N="Girder2_geometry" T="Group" Extends="Girder1" X="64*1" Y="-99*1" />
    <O N="u43ch0" T="Sensor" X="-100">
        <P N="output" V="Strain" T="Text" />
        <P N="install" V="2014-01-01 00:00:00" T="Text" />
        <P N="remove" V="None" T="Text" />
        <O N="u43ch0_geometry" T="Volume"
            X="64+EndSpanLength+22*6+ExpansionLength+MiddleSpanLength/2"
            Y="-95" Z="-25">
        <!-- omitted -->
```

(a) Augmeting Existing Object with Parameters (b) Defining and Appending New Object

Fig. 12.5 Defining entities and attributes for SHM BrIM schema

12.2.2.1 A Bridge Information Modeling (BrIM) Framework

The purpose of an engineering information model is to provide a semantic representation of the physical system, its components and any relevant information about the system. Adhering as much as possible to industry standards and practices, our goal is to develop a bridge information modeling (BrIM) schema that is able to support SHM applications [Jeong et al. (2017)].

The BrIM schema builds upon the prior effort on the OpenBrIM standards advocated by the Federal Highway Administration (FHWA) as an information modeling standard for the digital description of bridge structures [Chen and Shirolé (2006); Bartholomew et al. (2015)]. The OpenBrIM schema uses ParamML, an Extensible Markup Language (XML)-based syntax, to represent a bridge structure as a set of hierarchical objects with parameters [ParamML (n.d.); OpenBrIM (n.d.)]. OpenBrIM includes a collection of pre-defined objects to define the geometry of a bridge structure and project related information. The BrIM schema extends the OpenBrIM standards by using a commercial bridge modeling and analysis tool, namely CSiBridge [Computers & Structures, Inc. (n.d.)], as a base to define data entities that are needed for engineering modeling and analysis of bridge structures. Furthermore, we draw upon open standards, namely SensorML [OGC (2014)], for describing sensors and measurement information to develop a more comprehensive BrIM schema for SHM. As shown in Fig. 12.5, the BrIM schema augments the OpenBrIM standards with two main types of extension: (1) appending additional parameters to certain existing objects in the OpenBrIM standards, and (2) defining new objects needed to represent engineering models and sensor information.

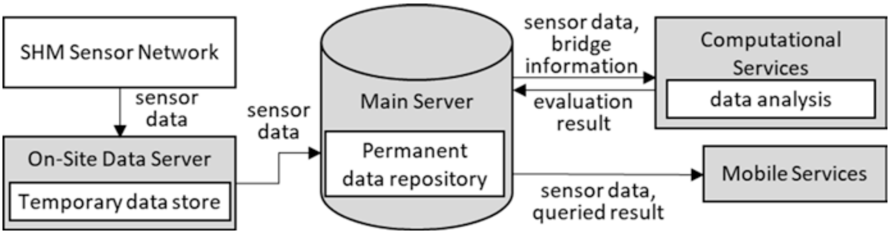
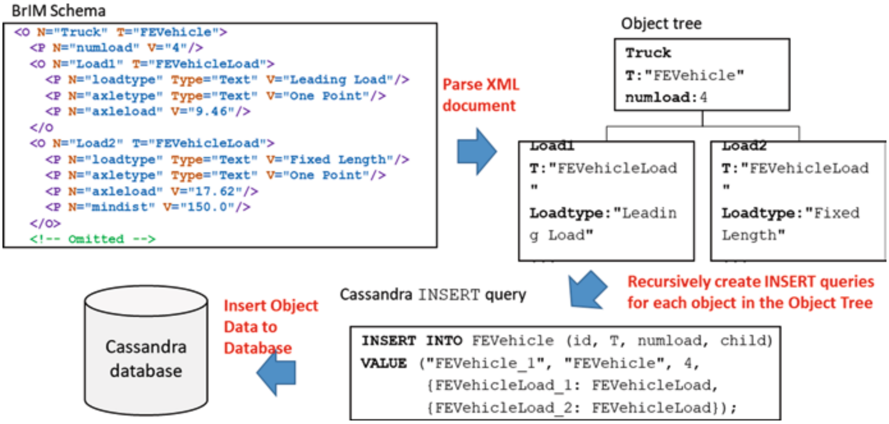


Fig. 12.6 Data management framework for a SHM system

12.2.2.2 A Data Management Framework

A data management framework is designed to capture the basic characteristics and functions of a SHM system [Jeong et al. (2019a); Jeong et al. (2015)]. As shown in Fig. 12.6, a typical SHM system consists of three main components: an onsite (data acquisition) server collocating at the physical system instrumented with sensors, user/client computing devices (local desktops or mobile devices) for accessing and processing the collected data, and a main server housing the data and application services. The onsite server receives measurement data from sensors and transfers the data to the main server, which resides either on premise within an organization or on a cloud platform. The main server hosts a persistent database system that stores the measurement data along with other information (such as bridge geometry model, engineering model and sensor information) that are relevant to SHM. The discussion herein focuses on the selection and implementation of a database system for the SHM platform.

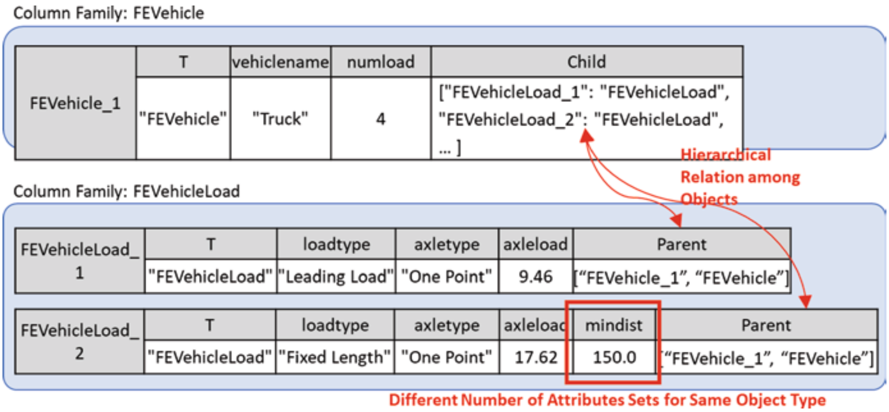
The CPS framework is positioned to collect massive amount of data with analytics performed in real-time or near real-time desired by the applications. As a result, a scalable data management system that is interoperable with established domain data standards and software is necessary at the core of the CPS framework. One option to consider is to employ relational database management systems (RDBMS) which are reliable, cost-effective, and offer rich query languages [McNeill (2009)]. However, RDBMS systems are limited in their scalability and do not offer high-speed data query interfaces when contending with massive amounts of sensor data [Jeong et al. (2016)]. An alternative to the classical RDBMS is a new generation of non-relational, or NoSQL (Not Only SQL) database platforms. NoSQL databases are designed to handle unstructured data such as those found in engineering models and structural monitoring systems. In this work, NoSQL database management system is adopted because of its scalability in both data storage for heterogeneous data and query speeds. The NoSQL database is designed not only to support the management of bridge monitoring data but also to facilitate data utilization by engineering design and analysis platforms. Based on the needs of the data management framework, Apache Cassandra is selected as the backend database system on the main server to support persistent data store and efficient querying [Moniruzzaman and Hossain (2013)].



```
<O N="Truck" T="FEVehicle">
  <P N="numload" V="4"/>
  <O N="Load1" T="FEVehicleLoad">
    <P N="loadtype" Type="Text" V="Leading Load"/>
    <P N="axletype" Type="Text" V="One Point"/>
    <P N="axleload" V="9.46"/>
  </O
  <O N="Load2" T="FEVehicleLoad">
    <P N="loadtype" Type="Text" V="Fixed Length"/>
    <P N="axletype" Type="Text" V="One Point"/>
    <P N="axleload" V="17.62"/>
    <P N="mindist" V="150.0"/>
  </O>
  <!-- Omitted -->
```

```
INSERT INTO FEVehicle (id, T, numload, child)
VALUE ("FEVehicle_1", "FEVehicle", 4,
       {FEVehicleLoad_1: FEVehicleLoad,
       {FEVehicleLoad_2: FEVehicleLoad});
```

Fig. 12.7 Mapping of BrIM schema and casandra database



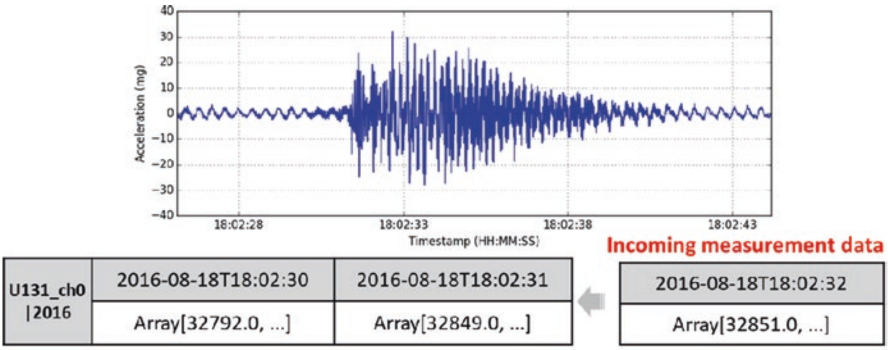
	T	vehiclename	numload	Child
FEVehicle_1	"FEVehicle"	"Truck"	4	["FEVehicleLoad_1": "FEVehicleLoad", "FEVehicleLoad_2": "FEVehicleLoad", ...]

	T	loadtype	axletype	axleload	Parent
FEVehicleLoad_1	"FEVehicleLoad"	"Leading Load"	"One Point"	9.46	["FEVehicle_1", "FEVehicle"]

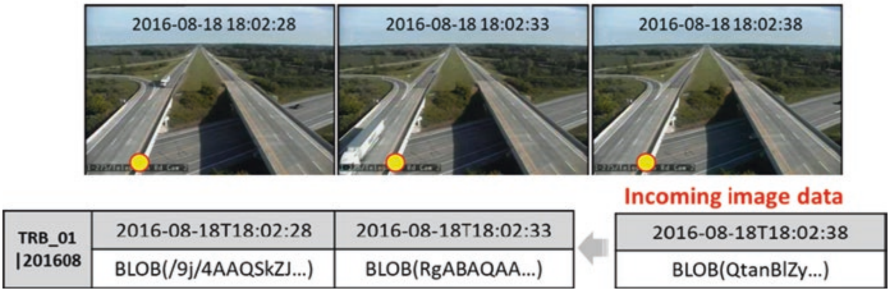
	T	loadtype	axletype	axleload	mindist	Parent
FEVehicleLoad_2	"FEVehicleLoad"	"Fixed Length"	"One Point"	17.62	150.0	["FEVehicle_1", "FEVehicle"]

Fig. 12.8 Mapping complex semi-structured BrIM data and casandra database

The column family data structure of Cassandra database offers many benefits for the management of SHM data. Cassandra database supports many data types, such as arrays, dictionary and others, that can be used in handling the heterogeneous data involved in SHM applications. This flexible data structure is beneficial when managing semi-structured data common to engineering applications. Firstly, as discussed, the bridge information represented in the BrIM schema is organized as a collection of hierarchically structured objects. Cassandra's flexible data structure is particularly effective in handling the complex and hierarchical bridge information [The Apache Software Foundation (2016)]. As illustrated in Fig. 12.7, the object-oriented, hierarchically structured BrIM schema encoded in ParamML can be parsed using an XML Parser and the resulting object tree can be inserted into the NoSQL Cassandra database. Secondly, an object in the BrIM schema may contain instances that have different sets of parameters. As shown in Fig. 12.8, Cassandra



(a) Appending Time Series Sensor Data to Casandra Database



(b) Appending Video Image Data to Casandra Database

Fig. 12.9 Mapping contiguous time series data and casandra database

database can elegantly handle such complex datasets by allowing different rows (FEVehicleLoad_1 and FEVehicleLoad_2) in the same column family (FEVehicleLoad) to have different sets of columns (attributes). Lastly, within a row in a Cassandra database, additional columns can be added easily, which are useful for handling sequential datasets (e.g., time series sensor data) [Hewitt (2010)]. Figure 12.9 shows the data schema for handling time series sensor data and video images.

12.2.2.3 A Cloud Service Computing Platform

The cyberinfrastructure system is designed to handle very large volume of data and a variety of SHM application services. This study explores the applicability of cloud computing services for SHM to allow “convenient, on-demand network access to a shared pool of configurable computing resources that can be rapidly provisioned and released with minimal effort or service provider interaction [Mell and Grance (2011)].” In the prototype system, the cloud services are implemented on a public cloud platform, Microsoft Azure (https://azure.microsoft.com/) [Le et al (2014)].

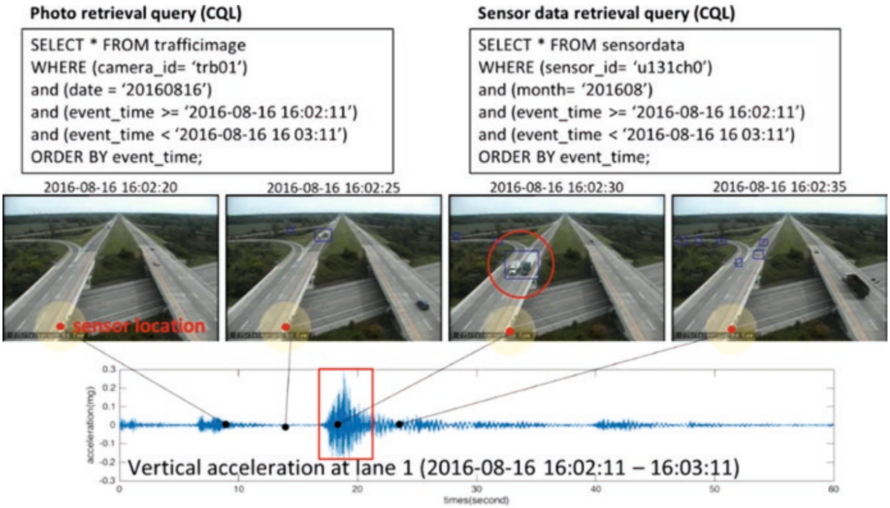


Photo retrieval query (CQL)

```
SELECT * FROM trafficimage
WHERE (camera_id= ‘trb01’)
and (date = ‘20160816’)
and (event_time >= ‘2016-08-16 16:02:11’)
and (event_time < ‘2016-08-16 16 03:11’)
ORDER BY event_time;
```

Sensor data retrieval query (CQL)

```
SELECT * FROM sensordata
WHERE (sensor_id= ‘u131ch0’)
and (month= ‘201608’)
and (event_time >= ‘2016-08-16 16:02:11’)
and (event_time < ‘2016-08-16 16 03:11’)
ORDER BY event_time;
```

Fig. 12.10 Retrieval of sensor and image data using CQL

Five cloud servers, each of which has 2 CPU cores and 16GB RAM, are employed for hosting the Apache Cassandra database. The distributed database system is designed to handle data partitioning and replication over the cloud servers to enhance system reliability. Data stored in the database system on the cloud platform can be accessed via either Cassandra query language (CQL) or web APIs. As a demonstrative example, Fig. 12.10 shows the retrieval of sensor data and the corresponding traffic monitoring images using CQL queries.

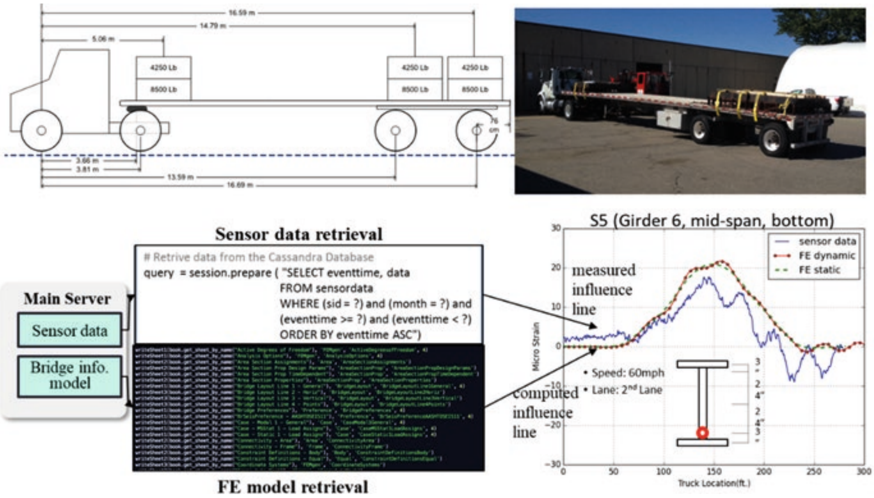
The example as shown in Fig. 12.10 illustrates the ease in accessing and integrating different data sets (i.e., camera frames and sensor data) to correlate bridge responses with specific truck events. Additionally, the cloud service platform employs RESTful web services, which have fast performance and high scalability, to facilitate data access from the database system. A variety of applications, including: data-driven analytics for sensor network and bridge monitoring and web/mobile user interfaces, have been developed [Jeong et al. (2019a, b, c)]. The web services are housed on three cloud servers, each has 2 CPU cores and 7GB RAM. The objective is to assess the scalability and flexibility of the distributed virtual machine environment for bridge monitoring applications. It should be noted that the user does not need to have the knowledge of the physical locations of the database servers and the application services housed on the cloud platform.

12.3 Illustrative Example Applications

The cyber infrastructure system allows seamlessly integration of engineering modeling information with a rich set of sensor data collected from the SHM systems, The computational infrastructure provides valuable platform to study the fundamental behavior of the bridges being monitored and to enable research on data-driven analytics for SHM applications. Selective examples are presented in this section to illustrate the potential applications of the CPS.

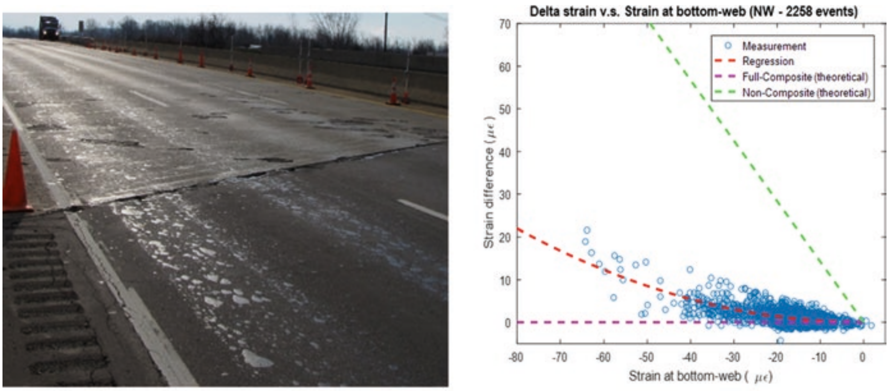
12.3.1 Influence Line Analysis

Influence lines, which represent the variation of structural responses at a specific location due to moving loads, are commonly used in the design of bridge structures [Wilbur and Norris (1948); Chopra (2017)]. Typically, influence lines are constructed analytically or simulated numerically using a structural analysis software. With the SHM system that can collect sensor data, we can easily compare the influence lines from the bridge response due to a moving truck and the analytically computed response using a finite element (FE) model. As shown in Fig. 12.11, the bridge information model is stored in the Apache Cassandra database in the cloud server. Furthermore, sensor data is collected and stored as a truck with known loads is travelling over the bridge. The FE model of the bridge structure is retrieved from the Cassandra database and analyzed with the known travelling truck load on a desktop computer. Finally, the measured and analytical bridge responses are compared by overlaying the obtained influence lines as shown in Fig. 12.11. As shown,



```
# Retrive data from the Cassandra Database
query  = session.prepare ( "SELECT eventtime, data
                           FROM sensordata
                           WHERE (sid = ?) and (month = ?) and
                           (eventtime >= ?) and (eventtime < ?)
                           ORDER BY eventtime ASC")
```

Fig. 12.11 Comparison of measured influence line and computed influence line



(a) Deck Spalling on North Abutment

(b) Strain differential at Concrete-Steel Interface and Strain at bottom flange

Fig. 12.12 Bridge composite action due to deck spalling

the measured response and the computational response are very similar, although the computational response shows slightly higher maximum response than the measured response.

12.3.2 Analysis of Bridge Deck Deterioration

Deck deterioration is a common problem observed on bridges. Figure 12.12(a) shows an example of the deteriorated deck on the TRB in 2010 (prior to the SHM instrumentation). A study is conducted to assess the bridge deck deterioration by analyzing the strain responses between the bridge steel girders and the 8-inch thick reinforced concrete deck to estimate the degree of composite action. As shown in Fig. 12.3, six locations along Girder 2 and Girder 6 are instrumented with BDI transducers bolted to the bottom surface of the bridge slab; and, at each location, three strain gauges are installed on the web 3 inches, 27 inches and 51 inches above the top surface of the girder bottom flange. Such an installation allows the profile of girder strain responses to vehicular loads to be estimated for the assessment of composite behavior exhibited at the girder-deck interface [Hou et al. (2019a)]. The differential strain between the bottom surface of the concrete slab and the top surface of the steel girder would be zero if the deck and girder are in perfect composite action and would be maximum when no composite action exists. Furthermore, the differential strain under no composite action, in theory, should scale linearly with load. Figure 12.12(b) shows the measured peak strain differential at the girder-deck interface and the corresponding peak bottom girder strain from over two years of observations with about 2000 truck events. As shown, nonlinear behavior, probably due to of the frictional forces developed on steel-concrete interface, is observed.

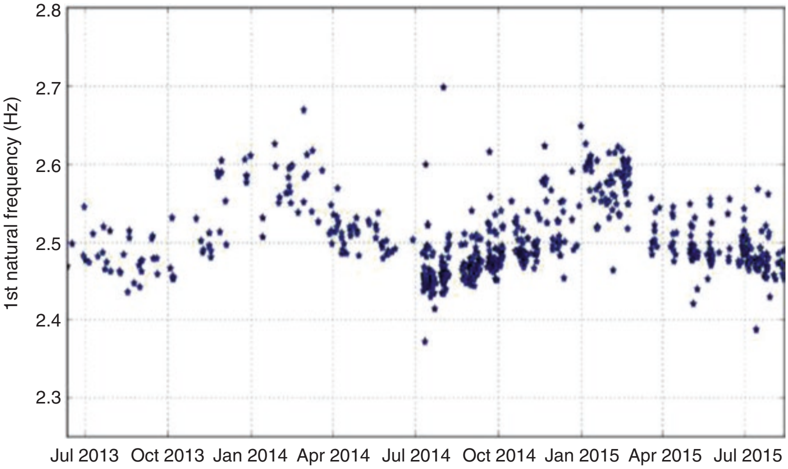
Through regression analysis, data-driven model capturing the composite behavior between the deck and the steel girders can be developed and employed to devise nonlinear spring elements for the FE model. Further analyses using the data-driven model conclusively show that the deterioration of the concrete deck over the bridge piers was due to partial composite action which was not accounted for during design [Hou et al. (2019a)].

12.3.3 Environmental Effects on Modal Frequencies

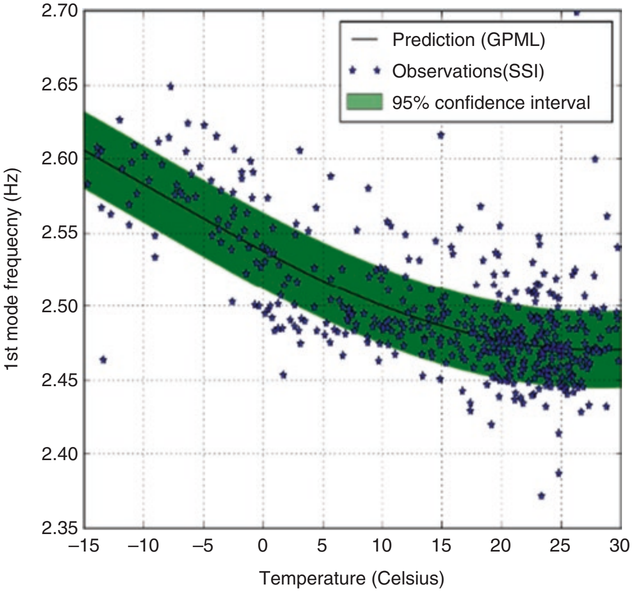
The long term monitoring data can also be used to understand the variation of structural behaviors due to environmental changes. In this example, we examine the changes in the natural frequencies due to the seasonal changes of temperature as illustrated in Fig. 12.13(a). Specifically, the sensor measurement data can be retrieved from the NoSQL data management system and Stochastic Subspace Identification (SSI) algorithm can be applied to extract modal properties from acceleration data [Hou et al. (2015)]. To establish the relationship between temperature and fundamental natural frequency, a regression analysis is conducted using the Gaussian Process for Machine Learning (GPML) module in scikit-learn (a Python-based machine learning package [Pedregosa et al. (2011)]) on a desktop. With the cyber infrastructure platform, the modal frequencies along with the temperature measurements can be easily accessed from the Apache Cassandra database. As shown in Fig. 12.13(b), while the analytic natural frequency is often assumed to be the same irrespective of the environmental changes, the data-driven regression model can be used to better estimate the fundamental frequency due to temperature changes.

12.3.4 Sensor Data Reconstruction

With the data collected from the testbed environment and stored on the cloud-based cyberinfrastructure, novel data analytics can be developed for a variety of tasks associated with characterizing bridge behavior as well as long-term health management of the sensor network itself. Generally, the data collected by the sensors in a sensor network commonly exhibits certain level of correlation among each other. Sensor data reconstruction methods leverage such correlation to estimate and to reconstruct the data of one or more specific sensors based on the data collected by the other sensors. Sensor data reconstruction has have at least two practical applications for the management of a sensor network [Jeong et al. (2019b)]. First, if one or more sensors are faulty, sensor data reconstruction can recover the data of the faulty sensors. Second, when the sensors operate normally, sensor data reconstruction can be used for anomaly detection by comparing the reconstructed and the measured data. Specifically, a study has been conducted to employ bi-directional recurrent



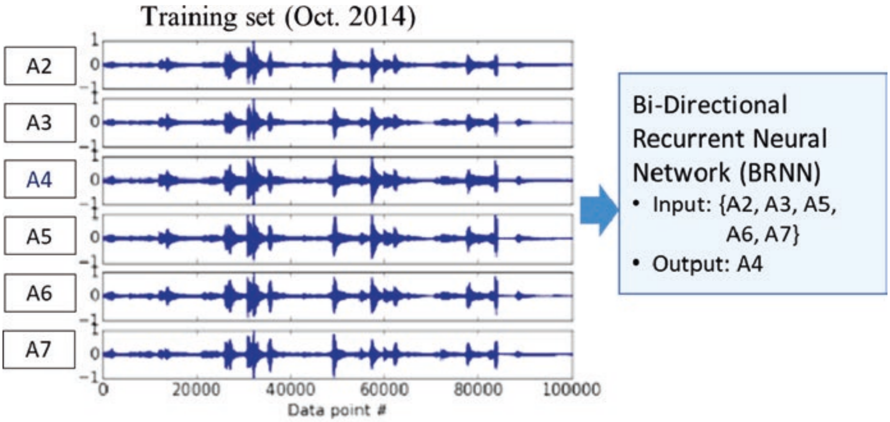
(a) Variation of Modal Frequencies over Time



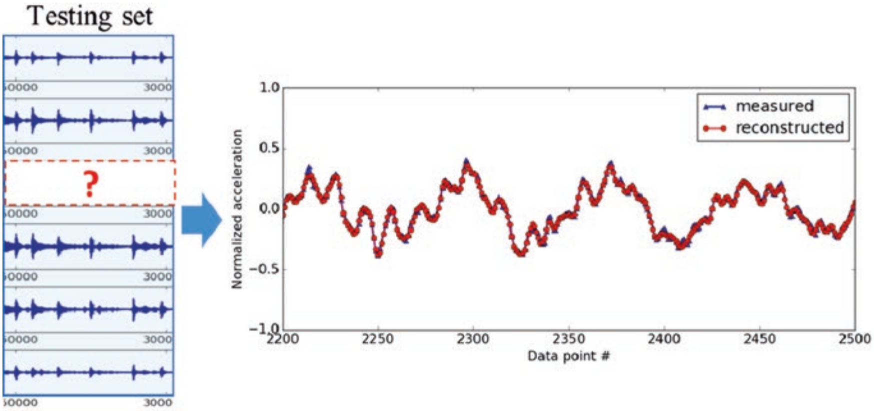
(b) GPRM for Modal Frequency vs Temperature Time

Fig. 12.13 Environmental effects on variation of modal frequencies

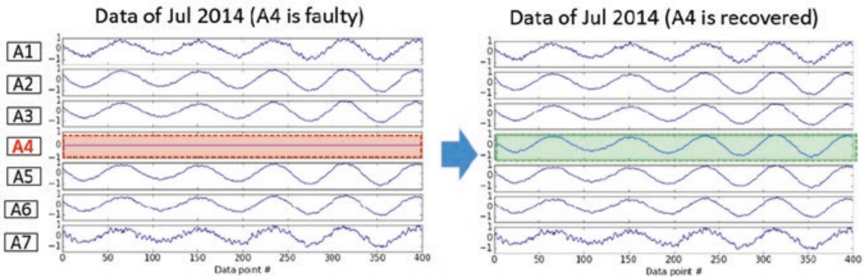
neural network (BRNN) to build prediction models for reconstructing time series sensor data [Jeong et al. (2019c)]. As shown in Fig. 12.14, the BRNN-based method is shown to be capable of reconstructing the sensor data. Furthermore, as shown in Fig. 12.14(c), the method is robust against environmental effects in that a BRNN



(a) Training of BRNN Model for Sensor Data Reconstruction



(b) Testing the BRNN Model for Sensor Data Reconstruction



(c) Recovering of Data for a Faulty Sensor

Fig. 12.14 Development of a machine learning (BRNN) model for sensor data reconstruction model trained with datasets from a certain month can be used to recover faulty datasets of other months.

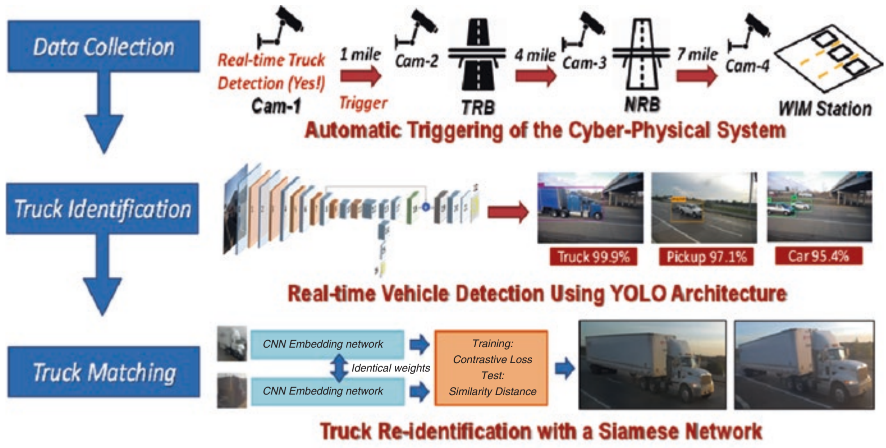
12.3.5 Computer Vision for Identifying Travelling Truck Loads

One key function of the CPS system is to provide a platform that new monitoring approach can be developed for real-time assessment of bridge infrastructure. As shown in Fig. 12.3, the highway corridor is installed with a weigh-in-motion station that can record valuable vehicle load information travelling through the corridor. Of particular interest is the ability to trigger the bridge SHM systems to collect data when a truck is crossing the bridge and to link bridge responses to the same truck passing through the WIMS station for measuring the truck loading. To achieve this goal, modern machine learning based computer vision algorithms running in real-time at each high-resolution traffic camera station is implemented to identify trucks [Hou et al. (n.d.)].

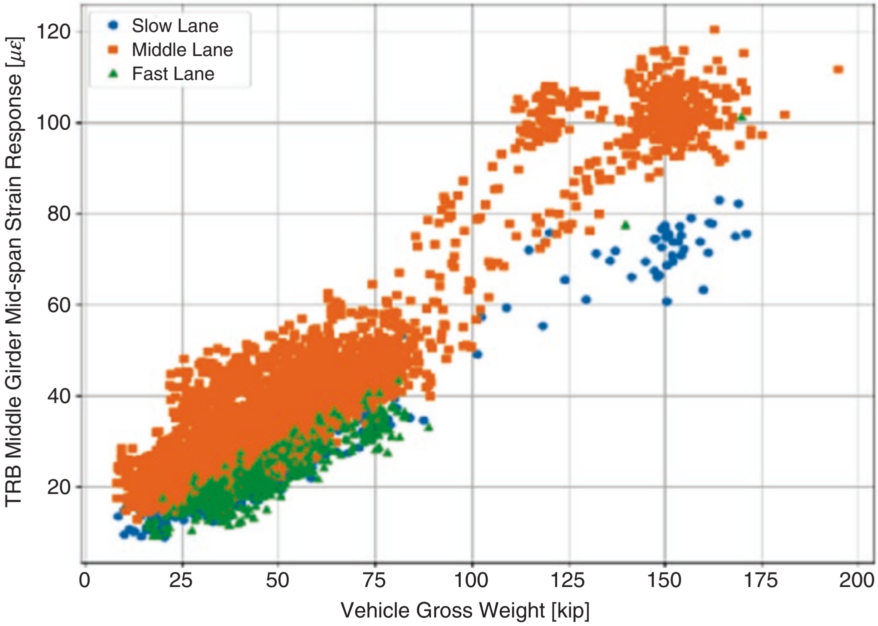
As shown in Fig. 12.15(a), a real-time truck detection model is developed utilizing an open-source deep convolutional neural network (CNN) algorithm named You Only Look Once (YOLO) [Redmon et al. (2016)]. The trained model is used to extract truck events from collected traffic cameras feeds. Truck images captured at the four locations along the highway corridor are automatically matched using feature extraction tool so that the same truck can be identified and tracked. By synchronizing the same truck travelling through the bridges and the WIM station, we can collect accurate truck loading and bridge response data for structural monitoring as depicted in Fig. 12.15(b). By leveraging the CPS, this research has led to a more accurate and practical approach for assessing the structural integrity of the bridge than the current approach that is based on empirically fitted models, for example, as described in AASHTO's Manual for Bridge Evaluation [Hou et al. (2019b); Hou et al. (2019c)].

12.4 Summary and Discussion

The key function of a CPS is to provide a platform that can provide real-time monitoring and assessment of a physical system. This chapter describes a CPS designed and implemented for structural health monitoring of bridges along a highway corridor. In addition to the sensing and monitoring systems instrumented on the bridge structures, the CPS takes advantage of the WIM station installed on the highway corridor and a network of cameras instrumented to capture and identify trucks passing through the corridor. To handle the amount of data involved in a CPS, a cloud-based computing platform is designed and implemented. Specifically, a NoSQL database system is deployed to implement the BrIM schema designed to



(a) A Triggering Strategy for Automated Truck Identification along Highway Corridor



(b) Correlation between bridge (strain) responses and WIM-measured truck weights

Fig. 12.15 A machine learning (YOLO) model for capturing truck loads and bridge response

capture engineering and sensor information. Furthermore, a cloud platform is leveraged for hosting the distributed database system and web services.

Selective examples, including influence line analysis, composite actions on bridge girders and environmental effects on natural frequencies, are provided to illustrate the utilization of the CPS platform to gain better understanding of the fundamental behavior of the bridge structures. With the repository of long term sensing and monitoring data, innovation data-driven models, taking advantage of the state-of-the-art developments in machine learning and computer vision, can be developed for structural monitoring applications, such as reconstruction of data from faulty sensors and accurate estimation and synchronization of truck loads and bridge responses. Research and development of these advanced data-driven models are possible because of the design and implementation of the CPS that includes both the bridge SHM systems and the cloud-based cyber infrastructure platform.

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Chapter 13
Cyber Physical Systems in Transportation: Traffic Management With Connected and Autonomous Vehicles

Lily Elefteriadou

13.1 Introduction

According to the National Institute of Standards and Technology (NIST)[1] "Cyber Physical Systems (CPS) comprise interacting digital, analog, physical, and human components engineered for function through integrated physics and logic. These systems will provide the foundation of our critical infrastructure, form the basis of emerging and future smart services, and improve our quality of life in many areas." Transportation CPS are highly dynamic, spanning spatial, temporal, and component dimensions. They operate in real-time, with humans-in-the-loop, where safety is paramount. Given the extensive evolution of autonomous and connected vehicle technology, there are additional emerging issues related to security, verification, and autonomy, among others.

The literature reports on various aspects of transportation CPS. Work and Bayen (2008) discuss how the mobile internet has been affecting the transportation system, where smartphones act as sensors with significant impacts in both traffic monitoring (phone-to-system data flow) and traffic information provision (system-to- phone data flow). Rawat et al. (2015) present a cloud-assisted GPS-driven dynamic spectrum access framework, to enhance reliability of communications for equipped vehicles. Xiong et al. (2015) discuss the social complexities of CPS, and present a transportation case study, examining travelers' decisions and behavior in a social context. Ekebede et al. (2016) examine the security of transportation CPS and present defense mechanisms for addressing both security and privacy. Hou et al. (2016), discuss simulation-based testing and evaluation of transportation CPS and

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[1] https://www.nist.gov/el/cyber-physical-systems

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present their three-in-one simulator which integrates traffic, network, and driver behavior aspects. Besselink et al. (2016) discuss the coordination of fleets of trucks traveling in platoons, and provide optimal planning and routing to reduce fuel consumption. Li et al. (2018a) developed a new car-following model for electric vehicles, considering communication with the infrastructure, and addressing lane discipline and no-lane discipline scenarios. Deka and Chowdhury (2018) provide a comprehensive overview of TCPS and consider a variety of topics including architectures, real-time control systems, and data management issues.

At the same time, advanced technologies related to autonomous vehicles (AV) have been under development by several automobile manufacturers and other entities. AVs have the ability to operate without a human driver using a variety of sensors such as GPS, LiDAR, radar, and smart cameras, as well as terrain and map information. Another set of technologies are being developed to support connected vehicles (CV), which are those that can communicate with surrounding vehicles and infrastructure using wireless communication such as Dedicated Short Range Communications (DSRC). AVs that also have the ability to communicate with infrastructure and each other are often referred to as automated vehicles or connected and autonomous vehicles (CAV). It is highly likely that in the not too distant future, both types of vehicles will operate side-by-side in large numbers on our nation's highways, alongside conventional vehicles that do not have such capabilities. Most recently, the US DOT's Federal Highway Administration (FHWA) has been developing the CARMASM Platform, which enables vehicles to communicate and cooperate with other vehicles. CARMA was developed using open source software and provides the opportunity to use vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) data connections for Transportation Systems Management and Operations (TSMO) initiatives. The Florida Department of Transportation (FDOT) is deploying an extensive list of projects related to CVs. One of these, the I-STREET (Implementing Solutions from Transportation Research and Evaluation of Emerging Technologies) real world test bed, a partnership of the University of Florida (UF) with FDOT and the City of Gainesville, Florida, involves extensive instrumentation to allow V2I connectivity in the area surrounding the University of Florida campus.

Given the extensive evolution of autonomous and connected vehicle technology, there is growing research on CPS that consider these advanced technologies, along with emerging issues related to security, verification, and autonomy, among others. For example, Fayazi et al. (2019) conducted experiments with a vehicle in the loop, for an all-autonomous intersection control scheme. Naufal et al. (2018) developed a new framework to design and implement an autonomous supervision and control system called autonomous automotive CPS, which aims to minimize the probability of collision hazards. A group at the University of Florida (Pourmehrab et al. 2019; Li et al. 2018a, b; Omidvar et al. 2018; Emami et al. 2017; Pourmehrab et al. 2017; Li et al. 2014; Omidvar et al. 2019; Gasulla and Elefteriadou 2019 and Letter and Elefteriadou 2017) have developed several algorithms for optimizing autonomous and connected vehicle trajectories to minimize travel time and maximize throughput. One set of algorithms (Pourmehrab et al. 2019; Li et al. 2018a, b; Omidvar et al. 2018; Emami et al. 2017; Pourmehrab et al. 2017; Li et al. 2014) has focused specifically on the joint optimization of signal control and autonomous/connected vehicle trajectories. Another set of algorithms optimizes CAV trajectories at bottleneck locations (freeway merges and roundabouts).

This chapter focuses on the principles, applications, deployment, and challenges of CAV CPS from a highway transportation systems management perspective. These types of CPS leverage communications, sensors, and other advanced technologies to improve the efficiency of the highway network in terms of travel times and throughput, in real-time, and with humans-in-the-loop. Such systems optimize and transmit recommended trajectories to those vehicles that can receive the information. These trajectories aim to increase throughput by minimizing the departure headways at bottleneck locations, and at the same time they reduce the system average travel time.

The next section discusses signal control CAV CPS, while the third section discusses freeway operations. The fourth section summarizes challenges for CAV CPS development and implementation, and the last section provides conclusions and recommendations.

13.2 Signal Control-Related CPS

Traditional signal control allocates the green time at a signalized intersection based on the proportional demands of the competing approaching movements. Simpler, older systems use pre-timed control: signal timing intervals are pre-determined, and do not vary based on real-time demand. For these systems, signal timings are estimated using historical data. More advanced systems, called actuated control systems, are those which use sensors to detect vehicle demand and modify signal control accordingly. Such systems detect vehicle arrivals using loop detectors, video, or other technologies, and set signal timings based on a pre-determined set of minimum and maximum green times for each approach or movement. However, the sensors (typically loop detectors) these systems use are often too close to the intersection for the signal controller to proactively anticipate vehicle arrivals and adjust signal timings accordingly. Also, the behavior of human drivers is highly variable, and difficult to predict: drivers may change lanes and turn left when the signal controller anticipates they will travel through the intersection. The advent of CV and CAV technologies allows for communication between vehicles and the signal controller, particularly to determine the vehicle's destination in advance, in order to be able to proactively modify signal timings. For CAVs, when they are able to receive and execute a trajectory without relying on a human driver, lost time can be minimized by scheduling their departure at a predetermined minimum headway and a predetermined maximum speed at the stop bar.

The CAV CPS described here takes advantage of the instrumented vehicles' ability to send information regarding their status and location, and to receive information regarding the network. A central controller receives all arrival information, and

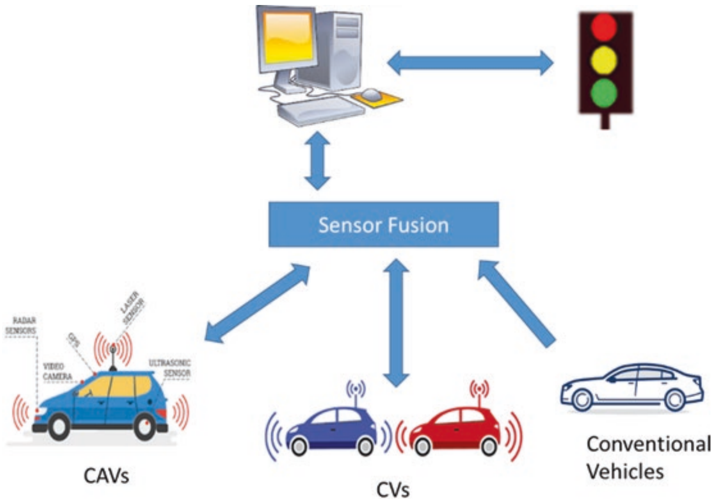

Fig. 13.1 Framework of CAV CPS for signalized intersections

optimizes signal control jointly with vehicle trajectories. Figure 13.1 illustrates the concept.

As shown, CAVs and CVs are able to send and receive information, while conventional vehicles can be detected by sensors such as video or radar. All arrival information is received and synthesized using sensor fusion in order to obtain the most accurate information for each vehicle. Vehicle arrivals from all approaches are monitored and the respective input is used to optimize the allocation of green to all approaches such that travel time is minimized and throughput is maximized. At the same time, the algorithm generates optimal trajectories for all vehicles able to receive it (CAVs and CVs). The sensors keep track of all vehicles approaching the intersection such that the algorithm can adjust the signal timings when vehicles do not follow the recommended or expected trajectory.

13.2.1 Development of Optimal Trajectories

Optimal trajectories are generated such that vehicle departures at the stop bar occur at the saturation flow rate (which corresponds to the minimum allowable headway; its value is typically around 1.8 sec/vehicle). This parameter can be adjusted based on the vehicle characteristics and safety requirements. For example, for CAVs that can operate at lower headways, capacity (which is the inverse of the minimum headway) will significantly increase as a result of reduced headways. This capacity increase will also hinge on the percent of CAVs traveling through the intersection, as conventional vehicles will typically maintain longer headways.

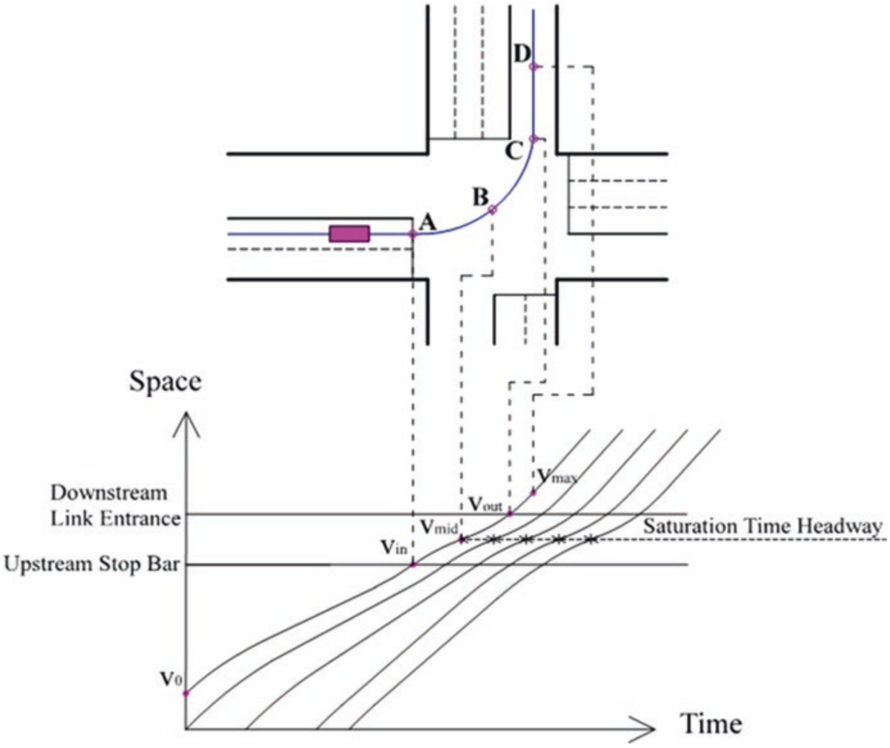

Fig. 13.2 Optimal trajectories for left-turning vehicles

Optimal trajectory determination also depends on the allowable speed at the stop bar. That speed will be higher for through vehicles and lower for turning vehicles. Figure 13.2 illustrates a series of optimal trajectories developed for left-turning vehicles. As shown, each vehicle departs the stop bar (point A) at the maximum speed, and then has to decelerate (point B) to negotiate the left turn. Once they reach the target lane, they can accelerate again (points C and D).

Estimation of optimal trajectories can be accomplished using different techniques. Li et al. (2014) optimized vehicle trajectories based on four components, in order to allow for adequate flexibility so that each vehicle can accelerate and decelerate along the path as needed. Feng et al. (2018) use optimal control theory to minimize fuel consumption and emissions. They indicate that their optimal trajectories consist of no more than three components. Pourmehrab (2019) develops trajectory functions based on several constraints (departure speed, acceleration range, jerk range) for each vehicle.

Generally, in order to maximize throughput and minimize travel time, trajectory optimization should maximize the departure speed at the stop bar, and minimize the departure headways (saturation headways, or minimum headways). Additional optimization criteria may include fuel consumption and emissions.

Reservation-type CPS [see for example Dresner and Stone 2004, 2008] do not require the development of optimal trajectories, as the CPS divides an intersection conflict zone into reservable tiles and books them on a first-come-first-served basis. In this case, vehicles receive a reservation time, rather than a trajectory.

13.2.2 Joint Optimization of Signal Control and Trajectories

Several approaches have been developed for optimizing signal control jointly with vehicle trajectories. Earlier efforts (for example, Li et al. (2014) simulated simpler intersections with only a few phases, and in those cases simple enumeration can provide an optimal solution. More complex, multiphase intersections, require more sophisticated optimization methods.

Li et al. (2018b) used genetic algorithms (GA – uniform crossover technique) to jointly optimize signal control and vehicle trajectories for a four-leg signalized intersection with a total of twelve possible movements. The GA ran for 20 generations, with a population size of 100. The algorithm was implemented in Java, and produced the optimal vehicle passing sequence, the optimal vehicle trajectories, and the average travel time delay for each analysis interval.

Yang et al. (2016) used a branch and bound algorithm to determine the optimal departure sequence and optimal speed for a bi-level optimization problem. The upper level model optimizes the vehicle departure sequence, while the lower level produces optimal trajectories for CAVs. Guo et al. (2019) use dynamic programming with shooting heuristic as a subroutine for trajectory optimization. Pourmehrab (2019) used the minimum cost flow (MCF) model, which finds the set of unordered phases that would satisfy the demand, and then orders them to obtain green time allocations.

It is not clear whether one of those approaches is preferable to the others, and whether their assumptions would allow for a comparison on the same platform, and for the same scenarios. Nevertheless, all approaches report significant travel time and throughput changes, and intersection performance improves with higher CAV market penetration rates for all models.

13.2.3 Optimization Process

The optimization process and its frequency are important components of a CAV CPS, particularly during the deployment stage, as CAVs must be detected in real-time. In contrast to simulation, vehicles continue to move after being detected, while the algorithm must calculate and transmit optimal trajectories (deployment issues are discussed later in this section). Figure 13.3 (Li et al. 2014) illustrates the

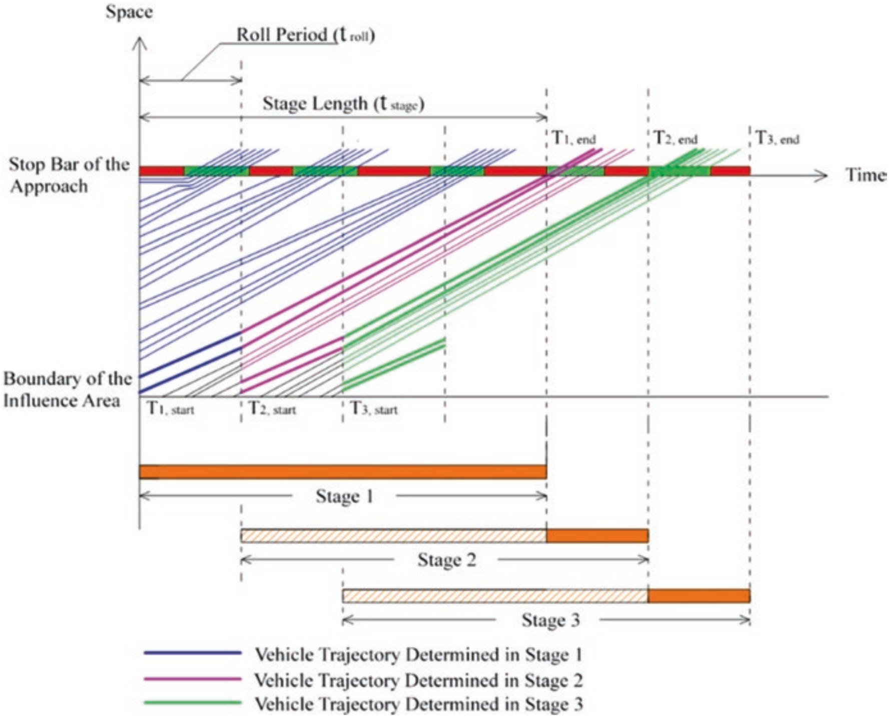

Fig. 13.3 Optimization process

optimization process in a time-space diagram for one of the signalized approaches to an intersection. As shown, vehicles are detected at the boundary of the communication, or influence area (the intersection of the vertical and horizontal axes). During each time interval Ti, the algorithm considers the arrivals from each approach and estimates the optimal signal timings for a later time interval, considering the travel time required for vehicles to reach the stop bar. In the example of Fig. 13.3 each stage provides the entire set of trajectories from arrival to departure for each set of arrivals during Ti. The longer the distance between the stop bar and the communication area, the more flexibility the algorithm has to plan for optimal signal timings.

As shown in Fig. 13.3, the optimization can reorganize vehicle departures such that all vehicles depart during the green, and no vehicle has to stop. Of course, when demand exceeds the capacity of the intersection (given the minimum headway allowable), queues will begin to form and at least some of the vehicles will have to stop, potentially upstream of the communication area.

13.2.4 Incorporating Conventional Vehicles

Several of the papers cited (Pourmehrab 2019; Yang et al. 2016; Guo et al. 2019) also consider the presence of conventional vehicles. One of the complications with conventional vehicles is that drivers are unpredictable. These algorithms make assumptions about the trajectories of conventional vehicles, but it is not clear how robust the algorithms are when assumptions regarding the movement of conventional vehicles do not hold. Pourmehrab (2019) provides a feedback loop in the optimization process such that trajectories and signal control can be adjusted when vehicles do not follow the anticipated or recommended trajectory.

13.2.5 Other Considerations

One of the key issues in the effective deployment of the CAV CPS described here is the communication range. The distance at which vehicles are detected must be long enough for the algorithm to be able to detect them and generate optimal trajectories (Fig. 13.4). Given that the algorithm allocates green times to competing approaches, detection should occur over an interval (Δt) long enough to aggregate several arrivals from all approaches. As shown in Fig. 13.4 (left side) the first vehicle detected during Δt travels some distance by the time the last vehicle in the interval is detected

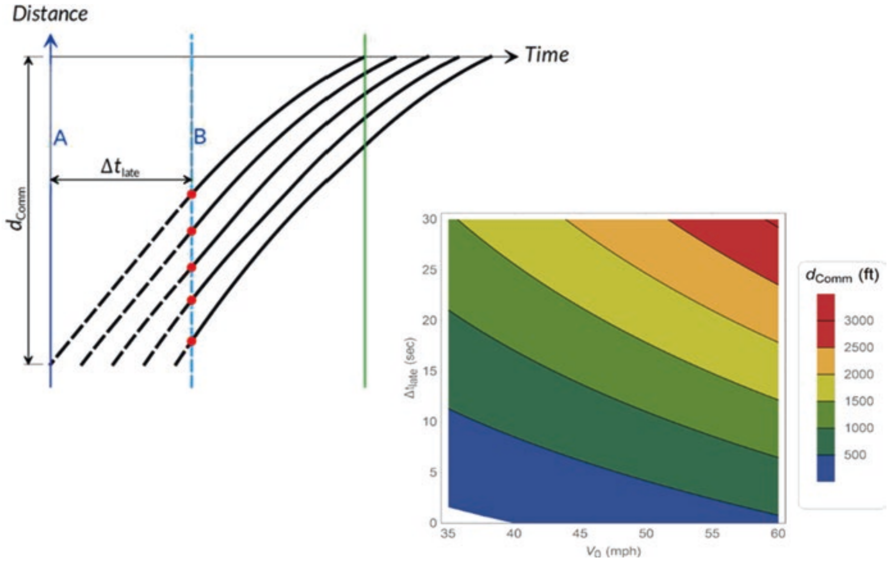

Fig. 13.4 Communication range, optimization interval, and approach speed

and the algorithm optimizes signal control and vehicle trajectories. The longer Δt is, the longer the first and subsequent vehicles travel. Also, the higher the speed of the approach, the longer the travel distance for those vehicles will be. Shorter communication ranges do not allow adequate time for vehicles to receive and execute the recommended trajectories. The right side of Fig. 13.4 illustrates the relationship between approach speed, Δt, and the feasible communication range. For example, for an approach speed of 50 mph, if the communication range is 1200 ft., then Δt must be no longer than 15 seconds. Conversely, for Δt equal to 25 sec, the communication range should approach 2500 ft. in order for the instrumented vehicles to be able to implement the recommended trajectories.

The signalized intersection CAV CPS described relies heavily on reliable sensors and communications between vehicles and the infrastructure. Preliminary deployment of the algorithms described (Omidvar et al. 2018; Emami et al. 2017) have relied on sensor fusion using video, radar, and DSRC. In order for these systems to be successfully deployed, reliability of the sensors and the communication system, as well as security are essential.

When conditions become congested for one or more approaches, the algorithms described cannot handle the demand. In those cases, some vehicles may have to slow down significantly or stop. As of this writing, there are no publications that consider the effect of congested conditions at the systems level. Also, there are no publications that consider jointly optimal trajectories and signal control at the arterial or network levels. Existing publications do not consider the effects of lane changing within the communications area. Lastly, there has been no consideration of pedestrians, bicycles, and scooters in the existing CAV CPS for signalized intersections.

13.3 Freeway Operations and CAV CPS

There is a limited number of publications focused on CAV CPS for freeways. There are several merging assistance algorithms that have been developed considering varying degrees of automation and communication capabilities (Letter 2017). For example, Daamen et al. (2011) used a roadside unit and satellite imagery to relay appropriate headway values to mainline vehicles,. Their results showed increased throughput and reduced travel times. Baselt et al. (2014) developed a merging order calculator based on fairness of the merging order. Simulation results were positive even for a low percentage of participating vehicles. These types of algorithms mostly focused on undersaturated roadway conditions, and on providing a safe and manageable merging scenario. More recent research on CAV CPS for freeways, aims to develop optimal trajectories for CAVs as they navigate a typical bottleneck such as a merge or weaving area. These are described briefly in the following paragraphs.

Fig. 13.5 CAVs at a freeway merge [26]

13.3.1 *Freeway Merge Areas*

Figure 13.5 (Letter 2017) illustrates a freeway merge with three mainline freeway lanes and one ramp lane. Such configurations often become bottlenecks along the freeway, as the approaching demand of 4 lanes must exit through 3 lanes. Given that traffic generally gravitates toward the rightmost lanes, these locations become the trigger for congestion and stop-and-go conditions. With CAVs in the traffic stream, traffic can be rearranged toward the leftmost lanes and suitable gaps can be created to allow for smoother merging of the on-ramp traffic. This requires communication capabilities similar to those described earlier for signalized intersections in the vicinity of the merge. In this case, the algorithm can maximize throughput by scheduling departures past the acceleration lane at the minimum discharge headway and the maximum possible speed. The resulting trajectories can be optimized such that each vehicle's travel time is minimized.

Letter and Elefteriadou (2017) developed an algorithm to optimize CAV trajectories through a freeway merge. Their algorithm generated an optimal trajectory for each arriving vehicle to maximize their average travel speed subject to the processing order, minimum time gap allowed, and other assumptions. Their trajectories consist of several components with constant acceleration. One of the difficulties with the development of optimal trajectories for freeway merges is that the algorithm must create gaps for entering vehicles. Figure 13.6 (Letter and Elefteriadou 2017) illustrates the trajectory of a vehicle arriving from the mainline rightmost lane (blue solid line, upstream of the merge point). As a vehicle arrives from the on-ramp, the trajectory of the subject vehicle (orange blue line) is adjusted to create a suitable gap in order to accommodate this new vehicle. To implement this, the algorithm must provide rules for determining under what circumstances a vehicle's trajectory will be adjusted in order to create such a gap. In Letter and Elefteriadou (2017), the vehicle with the potential to arrive at the merge point first is given priority.

During uncongested conditions and for a section with a one-lane freeway and a one-lane ramp, the algorithm developed in Letter and Elefteriadou (2017) was found to be able to reduce travel time, increase average travel speed and improve throughput when compared to operations with conventional vehicles only. The

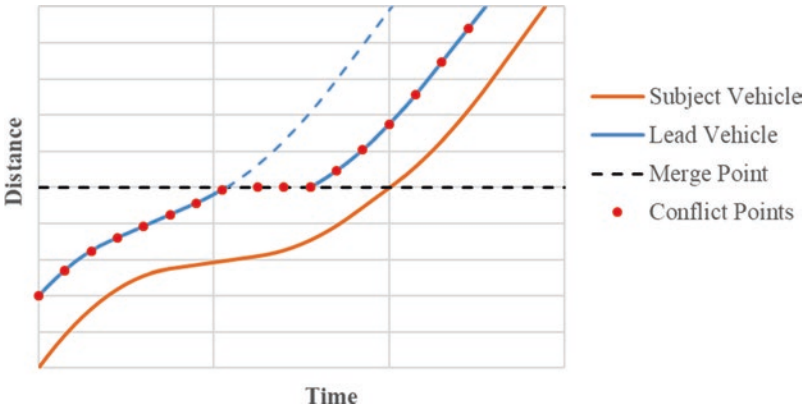

Fig. 13.6 Optimal trajectories for freeway merges

capacity of the merge segment is directly related to the safe time gap selected to run the algorithm. The authors indicate that the throughput was equal to the demand during undersaturated conditions, and equal to the theoretical maximum achievable value (which is a function of the safe headway) during oversaturated conditions. Once capacity is reached, queuing forms on both the ramp and mainline segments upstream of the merge area.

Figure 13.7 (Letter and Elefteriadou 2017; Letter 2017) illustrates trajectories around this merge area. Part A shows trajectories of conventional vehicles, while part B shows the same demand scenario for a CAV traffic stream. Blue lines represent mainline freeway vehicles and red lines represent on-ramp vehicles. As shown, with conventional vehicles there is a significant drop in speed at the merge (part A); however, with CAVs trajectories are smoother (part B) as their movement is planned in advance to accommodate arriving on-ramp vehicles.

In subsequent work, Letter (2017) expanded this algorithm to consider multilane freeways. For this revised algorithm, for oversaturated conditions the throughput did not reach the maximum theoretical value (it ranged from 100 to 200 veh/hr./ln below that value, which depends on the safe time gap/headway selected). When the demand exceeds capacity, queueing was observed on both the ramp and the mainline. The author indicates that queue length is a function of the relative ramp and mainline demands: in some cases there is no queue on the ramp, while in other cases the ramp queue is longer than that of the mainline. Adjustments to the algorithm may be able to function as a metering system, modifying priorities to minimize impacts to upstream facilities either for the mainline or for the ramp.

Similarly to the signalized intersection-related algorithms, reliability and security of sensing is essential. To-date, there is no discussion in the literature related to deployment of the CAV CPS described here. Also, existing work found in the literature has not examined mixed traffic effects (i.e., conventional vehicles with CAVs) at merges. System-wide effects of such strategies across a freeway network or along corridors of freeways and arterials have also not been explored in the literature.

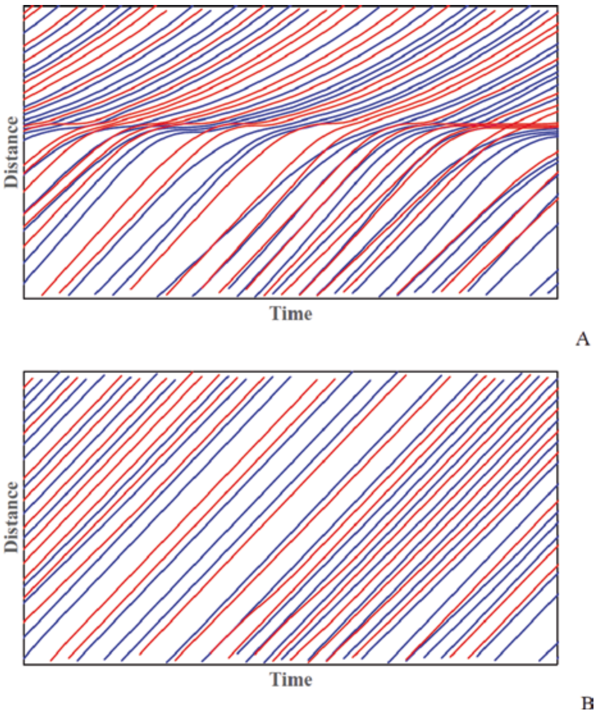

Fig. 13.7 Trajectories with conventional vehicles (**A**) and with CAVs (**B**) at a freeway merge

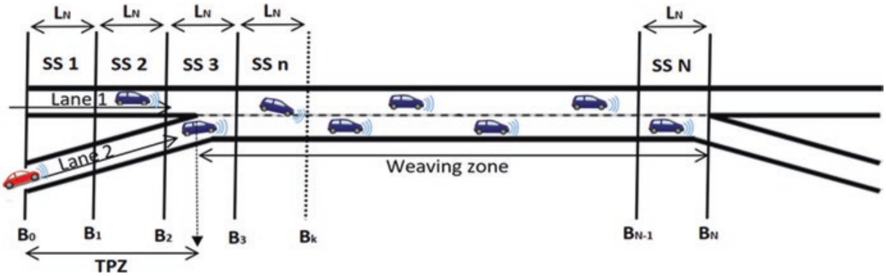

Fig. 13.8 Weaving operations with CAVs

13.3.2 *Freeway Weaving Areas*

Amini et al. (2019) developed an algorithm for optimizing operations for CAVs at freeway weaving areas. Weaving areas are those where an on-ramp is followed by an off-ramp and the two are connected by an auxiliary lane. Figure 13.8 (Amini et al. 2019) illustrates a weave along a one-lane freeway with an auxiliary lane. Their algorithm divides the weaving section into N short sub-sections (SS) each with length (LN). The optimization model minimizes the summation of the travel time in all those sub-sections considering the optimized trajectories of the vehicles already in the system and the minimum allowable headway. When a CAV enters the system, the algorithm identifies its destination, and the algorithm generates its optimal trajectory. Simulation results suggest that the proposed algorithm increases the average travel speed and throughput by 12 to 16% and up to 11%, respectively, when compared to conventional traffic (according to the Highway Capacity Manual 2016) estimates. Also, the algorithm increases the average speed by 17%, 30%, and 38%, for the minimum time headways of 1.7 s, 1.4 s, and 1 s, respectively, compared to conventional traffic operations.

There are currently no articles in the literature examining weaving operations for CAVs with mixed traffic, nor for freeways with more than one lane.

13.4 Roundabouts and CAV CPS

Gasulla and Elefteriadou (2019) developed a rule-based roundabout manager algorithm to decrease travel times and increase throughout for roundabouts with CAV traffic. The algorithm uses as input CAV arrivals from all approaches, and employs First-Come-First-Served (FCFS) priority rules to schedule each vehicle's departure considering possible conflicts within the circulating traffic area.

Figure 13.9 (Gasulla and Elefteriadou 2019) illustrates the roundabout traffic manager components. The large circle represents the communication area boundary. Once a CAV crosses this boundary it is within the control area and it begins to transmit pertinent information (its destination, speed, and vehicle characteristics, among others) and receive trajectory recommendations. Once the vehicle enters the management area (the smaller blue circle) its trajectory cannot be altered anymore, but it continues to transmit data related to its location and speed, which are considered for the trajectories of newly arriving vehicles. Once vehicles leave the management area through their desired exit leg, they are out of the system.

The management of vehicles in the roundabout is based on the virtual conflict sections (ci,i∈A) shown in Fig. 13.9. The algorithm prioritizes vehicles in a FCFS order at these conflict sections (rather than prioritizing based on the time vehicles enter the control area), considering the specific conflict sections a vehicle has to traverse given its origin and destination. The management system takes into consideration the geometry of the roundabout, including the flared entries and exits and the exact location of conflict sections.

The authors concluded that the algorithm is effective in reducing overall average delay per vehicle for all demand scenarios tested, particularly for higher-demand scenarios. However, the authors did not examine very high demand scenarios, nor impacts from having a mixed traffic stream (i.e., conventional vehicles and CAVs).

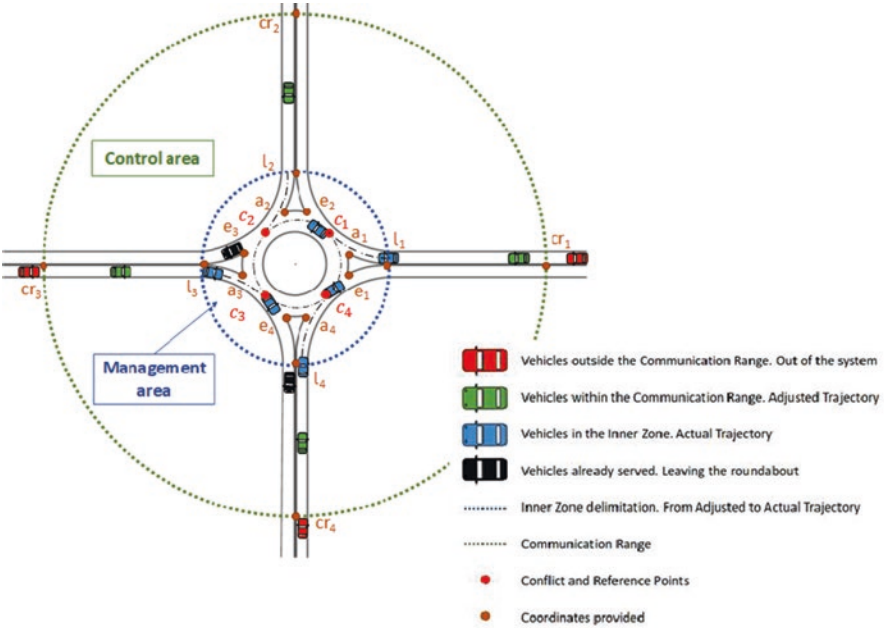

Fig. 13.9 Roundabout traffic manager

13.5 CPS Challenges for Transportation Applications

There are several challenges for CPS (Rajkumar et al. 2010). The following apply to transportation generally and to CAV CPS specifically:

Reliability and Security: These challenges are relevant for all types of CPS (Rajkumar et al. 2010) and particularly for transportation applications of the type discussed in this chapter (Gokhale et al. 2010). The algorithms referenced earlier rely heavily on the accuracy of vehicle detection, and the reliability of the sensors. They also rely on the communication range, speed, and reliability. Sensor fusion (Emami et al. 2017) has helped increase robustness for current deployments, but significant work still remains to prepare CAV CPS for successful deployment. Also, the CAV CPS must be resistant and resilient to security attacks.

Human Interactions with CPS: One of the most challenging aspects of traffic modeling and traffic management is the fact that human actions are highly variable and inconsistent. Each person reacts differently to each situation, generating a highly variable list of possible scenarios. To make matters worse, each of us is inconsistent in our reactions and our driving actions and decisions change based on the circumstances (for example, the gaps a particular driver accepts or rejects are not always the same; throughputs are higher in morning commutes than evening commutes). This creates an additional challenge for CAV CPS which relies on algorithms to make decisions related to traffic management. In order for these algorithms to be robust they should take into account human variability and inconsistency.

Modeling of CV and CAV: In order to be able to evaluate the feasibility of the algorithms described here and also test alternative scenarios, it is necessary to model CAVs in microsimulation. Traffic micro-simulators replicate the movement of individual vehicles in highway networks in order to evaluate alternative designs and demand scenarios. Conventional vehicle movement has been modeled extensively [Elefteriadou 2014]; however, CAV movement has not, as there is a variety of proprietary algorithms. Given these algorithms are not widely avail-able, they cannot be easily incorporated into traffic micro-simulators.

Calibration and Validation at the Systems Level: There is currently a lack of testbeds and integrated simulation platforms in order to evaluate CAV CPS comprehensively. Hou et al. (2016) developed a three-in-one integrated traffic, driving, and networking simulation platform, which is an initial step toward that direction. In the future, such platforms should be developed and expanded to allow for multiple human participants in the loop, they should allow for modeling of alternative novel CAV CPS, they should be able to replicate sensors and sensor fusion, and they should be able to model CV and CAV movement.

Education and training: CPS has been described as an intersection of several fields (Deka and Chowdhury 2018) and as such it presents unique challenges. It requires knowledge in several disciplines such as control theory, embedded systems, sensors, human factors, and others. Henshaw and Deka [Chap. 9 in Ref. 8] propose an educational program for Transportation CPS as well as delivery mechanisms. Given the extensive development in a wealth of advanced transportation technologies, as well as the interdisciplinary nature of transportation engineering, curricula should be developed and implemented to facilitate the transfer of knowledge for CPS from research to practice.

13.6 Conclusions and Recommendations for Future Research

In summary, there is a variety of Transportation CPS reported in the literature. The CAV CPS described here are able to leverage connectivity and automation capabilities in order to enhance mobility and safety. However, there are still several challenges before such systems can be widely deployed. In addition to the challenges described in the previous subsection, the algorithms described here should be enhanced in order to apply in a variety of scenarios.

Issues related to humans in the loop should be addressed, such that the algorithms described are able to adjust their output based on unanticipated actions of conventional vehicles. The algorithms should be able to react to pedestrians, bicycles, scooters, and generally unpredictable behavior by humans. Simulation modeling may be able to address many of the possible scenarios, however, the algorithms should be robust enough to be able to react to a variety of conditions, potentially via machine-learning applications.

The CAV CPS described here focus on specific bottleneck types and do not discuss system-wide effects. When the demand exceeds the nominal capacity (which is a function of the minimum headway selected), there will be a queue forming upstream of the communication area. Simulation of a freeway system including the area upstream of the bottleneck would be able to assess the impact of the CAV CPS of the type developed here at the systems level. Additional models and components for vehicle tracking are likely to be necessary in order to address interactions between successive freeway bottlenecks. Similarly, when evaluating an arterial corridor with several signalized intersections, it is necessary to develop arterial-level optimization models which would allow for the anticipated demand at a given approach, based on the discharge rates at the upstream intersection.

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Chapter 14
Role of CPS in Smart Cities

Jianping Wu and Dongping Fang

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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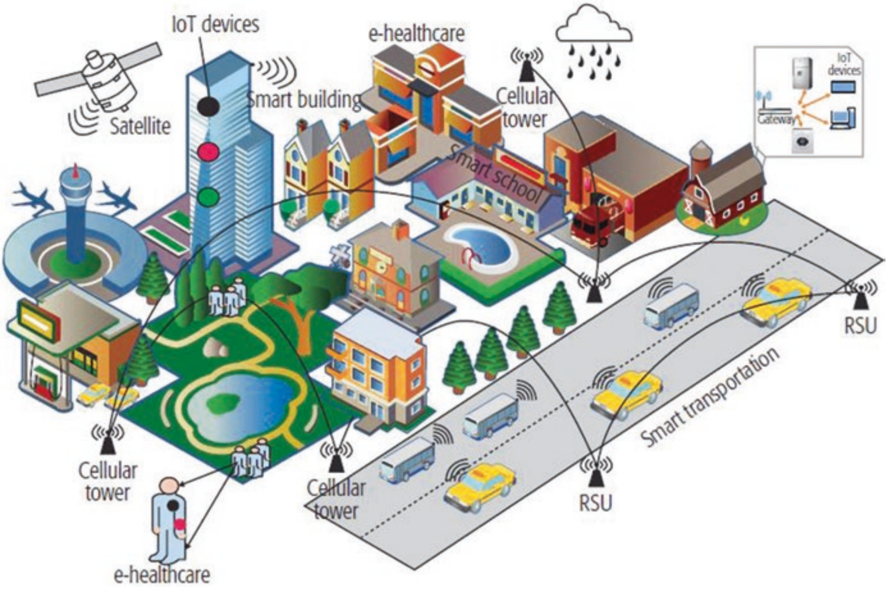


Fig. 14.1 An illustration of IoT based smart city (Mehmood et al. 2017)

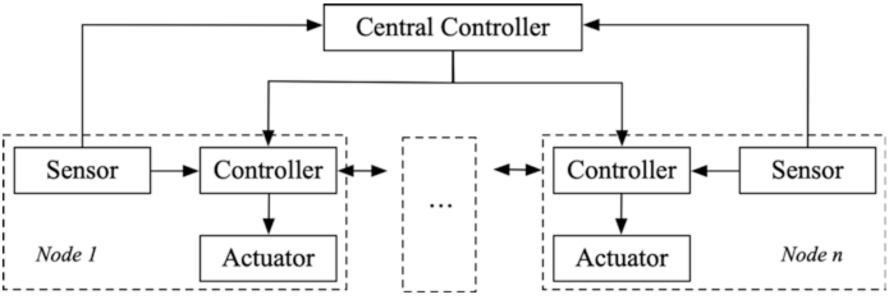


Fig. 14.2 Basic structure of CPS

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.

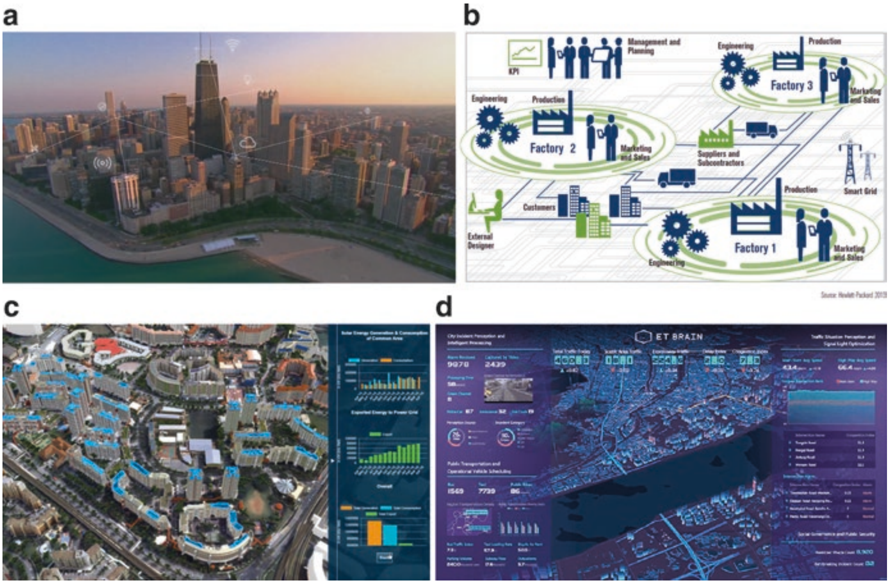


Fig. 14.3 Some smart city cases: (**a**) smart Chicago; (**b**) Germany; (**c**) Virtual Singapore; (**d**) ET City Brian

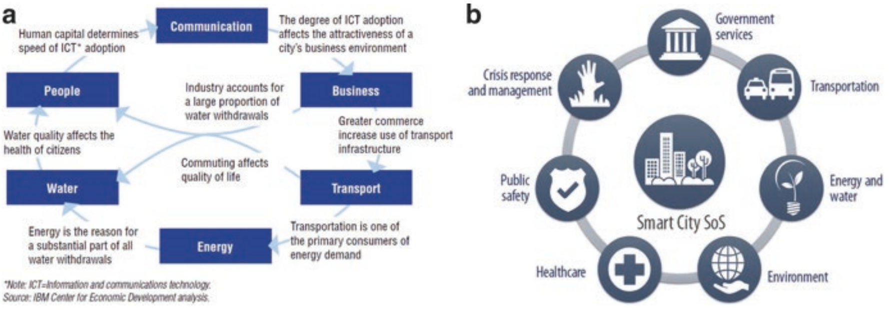


Fig. 14.4 Interdependency of CI, (**a**) Interrelationships between core city systems (IBM 2018); (**b**) Smart city SoS (Cavalcante et al. 2016)

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

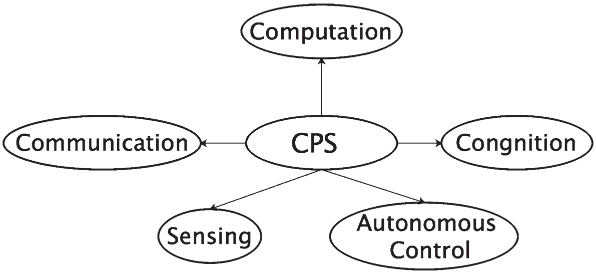


Fig. 14.5 Basic technologies of CPS

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	$\leq$ 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)	$\leq$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

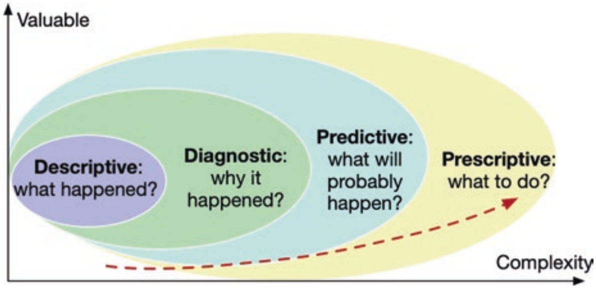


Fig. 14.6 Big data analysis

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.

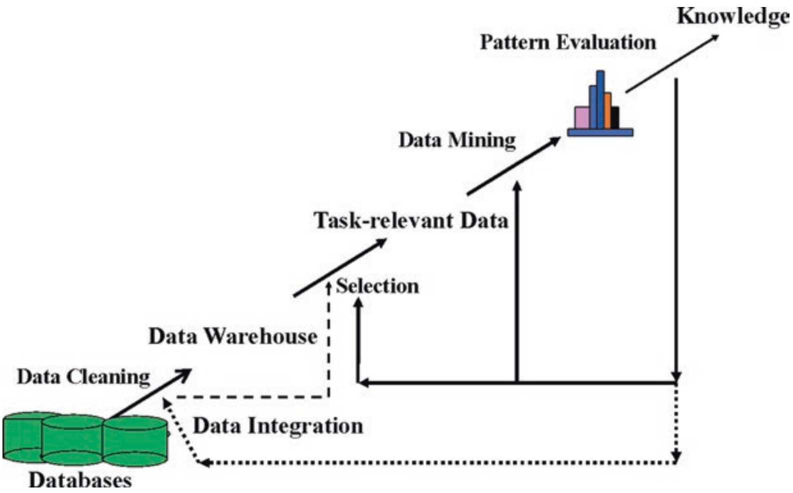
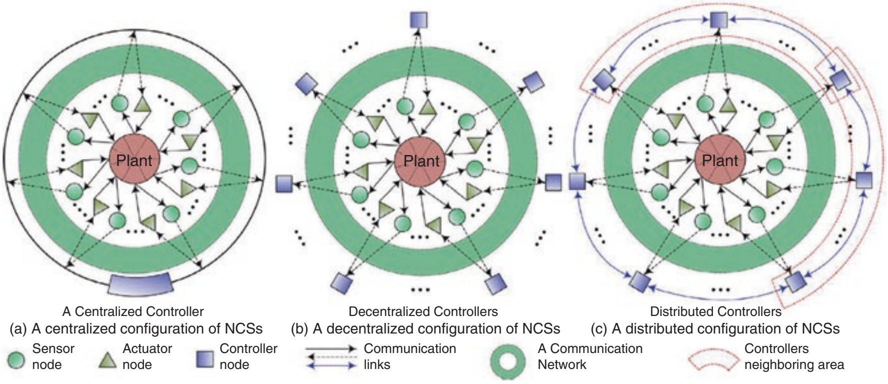


Fig. 14.7 Steps of the KDD process



(a) A centralized configuration of NCSs (b) A decentralized configuration of NCSs (c) A distributed configuration of NCSs

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

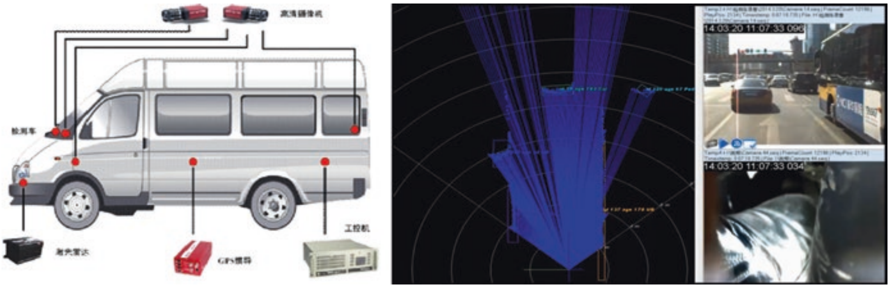


Fig. 14.10 Driving behavior's data collection equipment

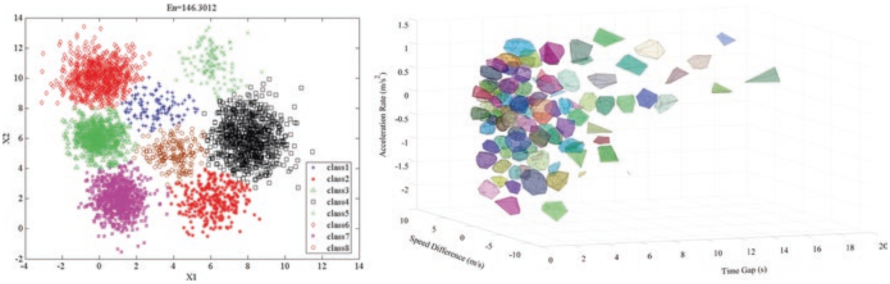


Fig. 14.11 Clustering of different driving behavior

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.

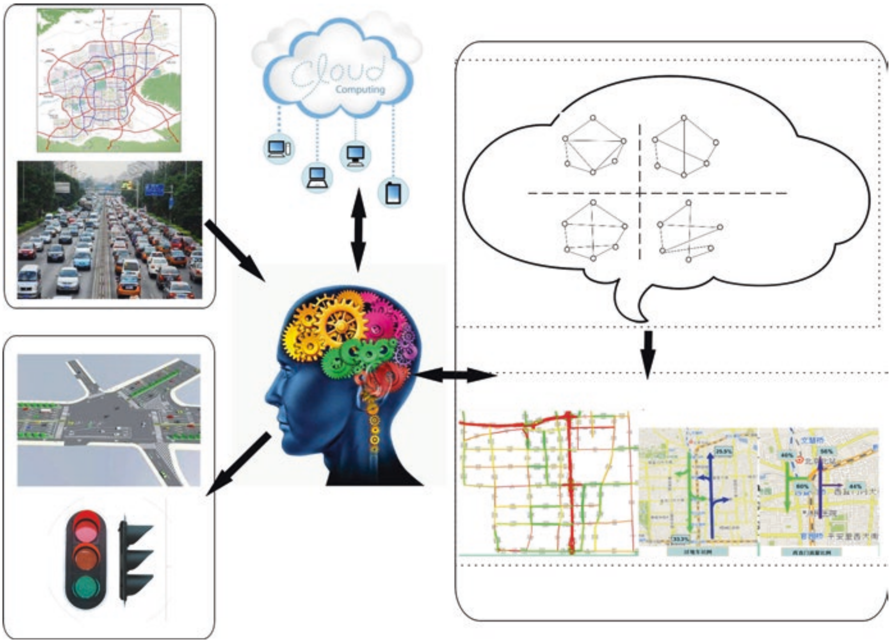


Fig. 14.12 Reinforcement learning of real-time signal control

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

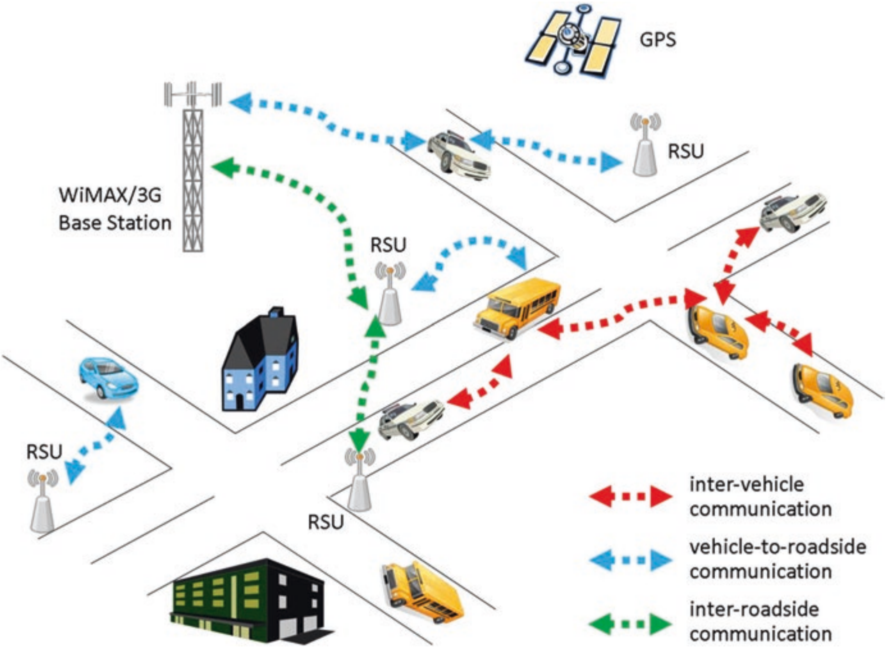


Fig. 14.13 An illustration of VANET scenario

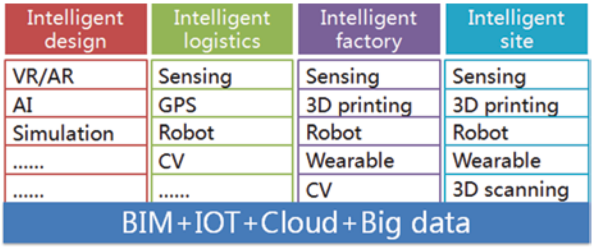
in routing. Latency, packet loss rate, and network load will have a significant impact on the network operation, which is still a hot academic issue.

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



Intelligent design	Intelligent logistics	Intelligent factory	Intelligent site
VR/AR	Sensing	Sensing	Sensing
AI	GPS	3D printing	3D printing
Simulation	Robot	Robot	Robot
……	CV	Wearable	Wearable
……	……	CV	3D scanning

BIM+IOT+Cloud+Big data

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

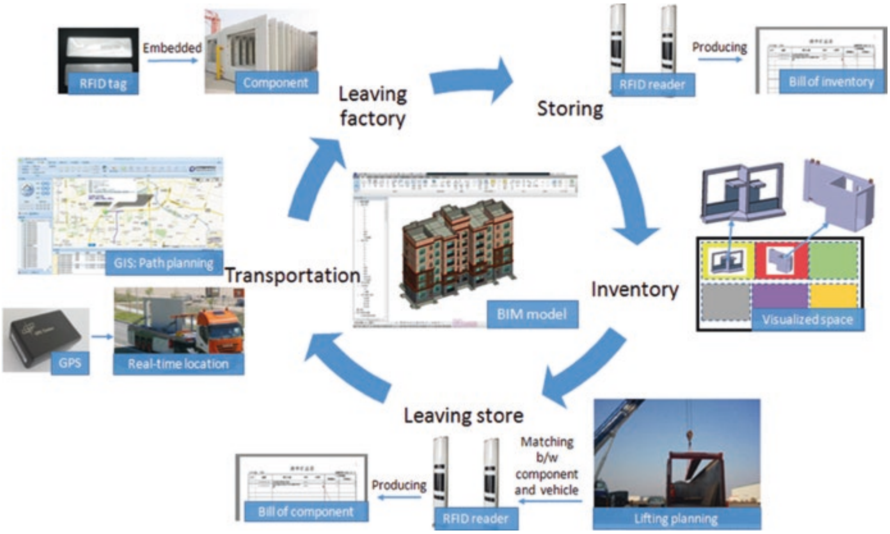


Fig. 14.15 A diagram for intelligent transportation of precast components

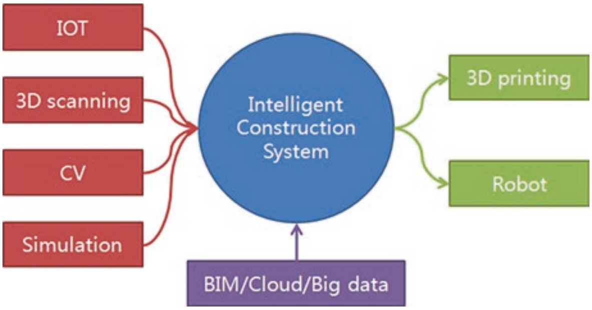


Fig. 14.16 The categories of key technologies of smart construction

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,

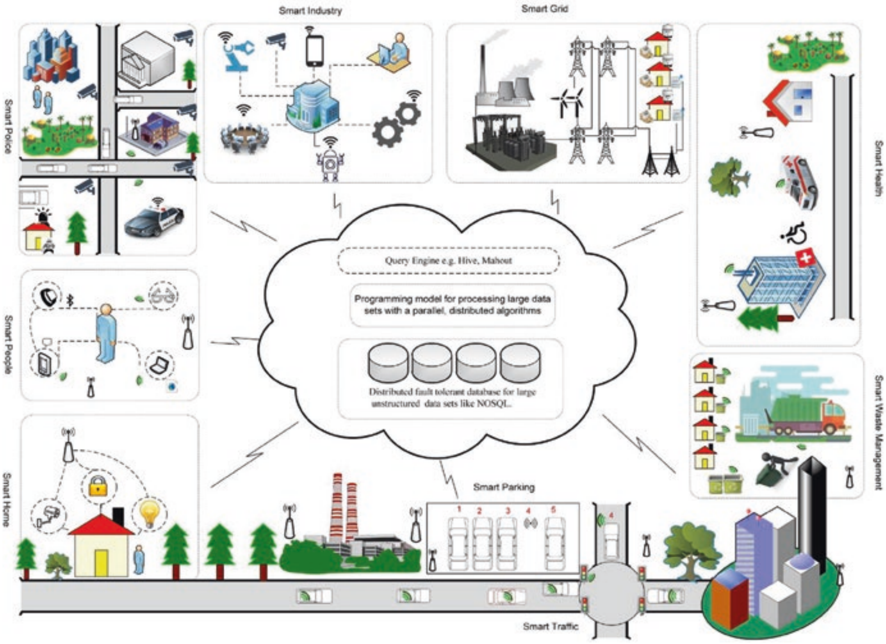


Fig. 14.17 Landscape of the smart city (Hashem et al. 2016)

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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Chapter 15
From Smart Construction Objects to Cognitive Facility Management

Jinying Xu, Weisheng Lu, Chimay J. Anumba, and Yuhan Niu

15.1 Introduction

With ‘smart’ becoming a buzzword around the globe, the enthusiasm for smart has infiltrated almost every aspect of life from the device level (e.g., smartphone and smartwatch), the industry level (e.g., smart health and smart transportation), to the city or country level (e.g., the smart city initiatives in New York, Seoul, Glasgow, Ontario, and Singapore). The Architecture, Engineering, Construction, and Operation (AECO) industry is no exception. It is strenuously exploring the concept of ‘smart’ to solve its many chronic problems such as escalating cost, delayed delivery, unsatisfactory quality, and stagnant productivity, as well as providing better services in the design, construction, installation, and operation stages. The smart era is driven by sensing, information and communication, computing, and automation technologies, which are becoming more powerful and pervasive than ever.

Pervasive sensing, information and communication, computing, and automation technologies make the bridge between the cyber and physical systems (CPS) buildable. Apart from the CPS, another dimension, the social dimension is also possible to be linked to form the cyber, physical, and social system (CPSS). CPSS tightly integrates sensors, actuators, data and information, computational resources, services, human beings, and so on from cyber, physical and social worlds (Somov et al. 2013). It extends the scope of CPS and takes the social characteristics of human

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beings into account to bridge the three worlds that have been largely isolated (Wang et al. 2017). As an emerging paradigm, CPSS has gained increasing popularity from the academia and industries by enabling deep fusion among social human beings, cyber computers, and physical things (Zeng et al. 2016b). To satisfy the requirement of human life, CPSS should contain handy sensing devices, networking facilities, computing facilities, actuating devices, and other equipment. The key techniques of CPSS include: (i) seamless migration technologies of various network, (ii) device management, (iii) context awareness, (iv) human-computer interaction, (v) user behavior based proactive service, (vi) social computing, and (vii) security and privacy (Zeng et al. 2016a).

Thanks to the progress in pervasive sensing technologies, Auto-IDs and sensors are getting more powerful in ability, cheaper in price and smaller in size, and has stimulated handling of the number of deployments (Sheth 2016) and promoted the Internet of Things (IoT) (Xu et al. 2019a). IoT allows people and things to be connected with anything and anyone at anytime, anyplace, ideally using any network and any service (Vermesan et al. 2011). With the rapid expansion, there will be more than 25–50 billion IoT devices deployed and 17–32 percent annual growth before this decade is over (Sheth 2016). It requires appropriate management for all these objects of IoT and their supporting technologies behind to overcome the technological heterogeneity and complexity, to better enhance situation awareness, reliability, and energy-efficiency in IoT applications (Foteinos et al. 2013).

Recently, there has been an emerging trend in cognitive IoT (CIoT). As a new network paradigm, CIoT is inspired by human cognition. In CIoT, real/virtual things are interconnected and interact as agents based on a situation-aware perception-action cycle (Wu et al. 2014). The things in CIoT are able to learn semantic and/or knowledge from kinds of databases, make intelligent decisions, and perform adaptive actions according to cognitive and cooperative mechanisms, with the objectives to promote smart resource allocation, automatic network operation, and intelligent service provisioning (Zhang et al. 2012; Wu et al. 2014).

The ability of CIoT is empowered by cognitive computing (CC), which can address interoperability and other aspects, such as hypothesizing correlations and validating them through evidence (Sheth 2016). CC is an interdisciplinary product of human cognition and computing machines. It is different from artificial intelligence (AI) by its fuzzy computing ability by mimicking the human thinking process in a computerized environment. It aims to achieve the low power, small volume, mind-like function, and real-time performance of the human brain (Xu et al. 2019b). With CC, a cognitive system can quickly learn and improve as it discovers knowledge and acquires profundity in complex environments (Xu et al. 2019b).

Moreover, communication, information, and actuation technologies are also highly advanced and pervasively used. For communication technology, LAN (local area network), WAN (wide area network), and WLAN (wireless local area network, including ubiquitously used WIFI, Bluetooth, Zigbee, and NFC), together form a complete communication network that can connect everything to the Internet. Some other emerging communication technologies such as WPAN (wireless personal area network) and WiMAX (Worldwide Interoperability for Microwave Access) will make communication more convenient and efficient. For information technology, computers and network systems, communication equipment and software, search engines, etc., are quite advanced to support FM. In the AEC/FM sector, BIM (building information modeling) is an emerging and increasingly popular information technology to support the management of buildings. As for computation technology, in recent years, technologies including big data, cloud computing, deep learning, machine learning, and cognitive computing are becoming more and more mature. Actuation technologies including wireless valve actuator, window opening/closing motors, relays for the HVAC (heating, ventilation, and air conditioning) systems are designed and produced and being pervasively used in daily life. With these supporting technologies, it is time to take a step forward to Cognitive FM.

The AEC/FM industry is embracing the rapid development of sensing, communication, information, computing, and actuating technologies to catch the fashion of ‘smart everything’. Among them, smart construction objects (SCO) (Niu et al. 2016a) and cognitive facility management (Cognitive FM) (Xu et al. 2019b) are proposed with a big blueprint. The concept of SCO is developed as a basic element to define, understand, and achieve smart construction (Niu et al. 2016a). The aim of Cognitive FM is to enable FM objects to see, listen to, smell, and feel the physical space for themselves, have them interconnected to share the observations, and beyond that, empower FM objects with a ‘brain’ to pervasive, think, and learn both the physical and social spaces by themselves for high-level intelligence (Xu et al. 2019b). However, there is a gap between smart construction and cognitive FM, as their development has been focused on different scenarios and stages. For a smarter integration of different processes of AEC/FM practices, the two pioneering concepts should be bridged for the overall ‘smartness’ of the built environment.

This chapter serves as an attempt to integrate SCO and cognitive FM by arguing that SCO will not only serve for smart construction purposes but can also remain in the objects for FM purpose; it is an enabler of cognitive FM. By their integration, information continuity and credibility, management continuity, and life-cycle management in AEC/FM projects for higher-level smartness. The rest of the chapter is organized as follows. Subsequent to this Introduction, Sects. 15.2 and 15.3 will introduce the definitions, properties, and frameworks of SCO and cognitive FM, respectively. Section 15.4 will discuss the necessity and feasibility of integration construction and FM, as well as the integration of SCO and cognitive FM. Section 15.5 will propose a framework of SCO-enabled cognitive FM, followed by Sect. 15.6 which explains the implementation of the framework by two illustrative scenarios. Section 15.7 discusses the challenges and Sect. 15.8 concludes the chapter and proposes some works that can be performed in the future.

15.2 Smart Construction Objects

15.2.1 Definition of SCO

'Smart construction' is conveniently used to refer to anything different from 'traditional' construction. For example, there is a 'smart construction site' where materials, machines, and workers can be tracked and monitored (Hammad et al. 2012); 'smart building construction' as an indispensable element of the smart city (Angelidou 2015); or 'smart construction lift car toolkit' that allows automated recognition of the logistic items in construction (Cho et al. 2011). Likewise, with the renaissance of interest in artificial intelligence (AI) and robotics for construction, several AI - or robotics-based systems have been developed under the nomenclature of 'smart construction'. These include the sensing system to monitor workers' exposure to vibrations (Kortuem et al. 2007), the contour crafting system for automatic building structures fabrication on-site (Khoshnevis 2004), or the mechanical arms to help worker handle heavy materials (Lee et al. 2006).

Despite the research efforts on smart construction by employing ideas from AI, robotics, and analogous concepts, there are still widespread frustrations in the industry in respect of smart construction. In contrast to the advanced development of smart systems in manufacturing, the automotive industry, civil aviation, and logistics and supply chain management, the fundamental concepts, definitions, and paradigms of smart construction are yet to be systematically explored. Successful cases of smart construction have emerged in a piecemeal fashion, having been developed for a specific trade and thus having little generalizability. In addition, smart systems introduced from other industries have been disruptive to existing construction practice, resulting in practitioner reluctance to harness their potential.

Based on previous studies of smart construction objects (SCOs), Lu et al. (2019) argue that the development of SCOs is leading towards a new paradigm of smart construction. It demonstrates that SCO development offers a perspective from which to (a) systematically define, understand, and achieve smart construction; (b) provide a new perspective to solve problems beyond the scope of existing paradigms; and (c) address limitations in existing studies on smart construction, including lack of theoretical lucidity, piecemeal application with limited generalizability, and the disruptive nature for deployment.

The concept of SCOs is developed as a basic element to define, understand, and achieve smart construction. Inspired by the concept of smart object (SO) (Kortuem et al. 2010, López et al. 2012), SCOs are proposed as a solution towards cognitive computing and intelligence in the AEC/FM context. They are defined as "construction resources made 'smart' by augmenting them with smart properties" (Niu et al. 2016a). These resources could be materials, components, tools, devices, machinery, and even temporary or permanent structures. To explain the smartness SCOs could confer, three core properties of SCOs are proposed in a tri-axial diagram (Fig. 15.1): awareness, communicativeness, and autonomy, denoting the sensing ability, data sharing ability, and autonomous action-taking ability of SCOs (Niu et al. 2016a).

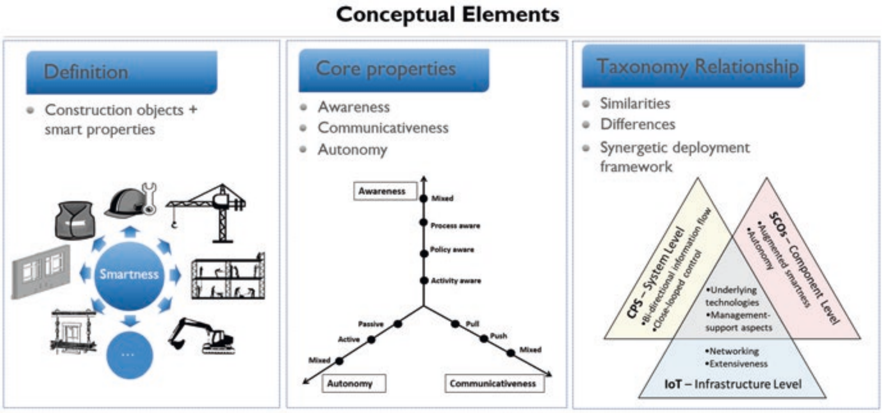

Fig. 15.1 The development of conceptual elements of SCOs (Lu et al. 2019)

Each of the three core properties is subdivided into several types, while they may function in cooperation depending on needs and requirements in different application scenarios.

15.2.2 Properties and Framework of SCO

As the basic elements of smart construction, SCOs offer a way to define and understand the paradigm of smart construction. Smart construction can be perceived as a paradigm for construction management by leveraging SCOs with their smartness, including awareness, communicativeness, autonomy, and other potential smartness to be enriched. Understanding of SCOs and the paradigm of smart construction is deepened when their taxonomic relationships with cyber-physical systems (CPSs) and the Internet of things (IoT) are elucidated (see Fig. 15.1). Differences and similarities between the three concepts are articulated by Niu et al. (2018). For example, although the three concepts share similar underlying technology tools, each operates at a different level (SCOs at the component level, a CPS the system level, and the IoT the infrastructure level) (Niu et al. 2018; Lu 2018). A synergetic deployment framework to integrate the three concepts has been proposed to harvest the synergy between them when adopting smart construction.

While flexible combinations of their three core properties (awareness, communicativeness, and autonomy) (see Table 15.1) enable SCOs to provide individual smart functions, the true power of SCOs lies in an integrated, responsive smart construction system in which they are linked. A generic framework for this SCO-enabled smart management system is developed for practical deployment (see Fig. 15.2). By providing a multi-layered structure with the connecting relationships in between, the system framework for the SCO-enabled smart management system clearly illustrates the process of turning traditional construction objects into smart and

Table 15.1 Properties of SCOs (adapted from Niu et al. 2016c)

Properties	Sub-dimensions	Explanations
Awareness – The ability of SCOs to sense and log the real-time condition of SCOs and the surrounding environment	Activity-aware	To understand and make record when certain type of activity or event is triggered
	Policy-aware	To understand to what extent the real-time a condition or activity comply with rules and regulations
	Process-aware	To understand and recognize the workflow and transition between construction activities
	Mixed	To have more than one type of above awareness
Communicativeness – The ability of a SCO to share information with managerial personnel or other SCOs	Pull	To provide information on requests
	Push	To proactively send updated information or mate alert in a regular interval
	Mixed	To have both pull and push communicativeness
Autonomy – The ability of SCOs to alert people for actions or to take autonomous actions	Passive	To make alerts to people and to assist people in along with decision and taking actions
	Active	To tate self-directed actions proactively based on change of conditions
	Mixed	To have both passive and active autonomy

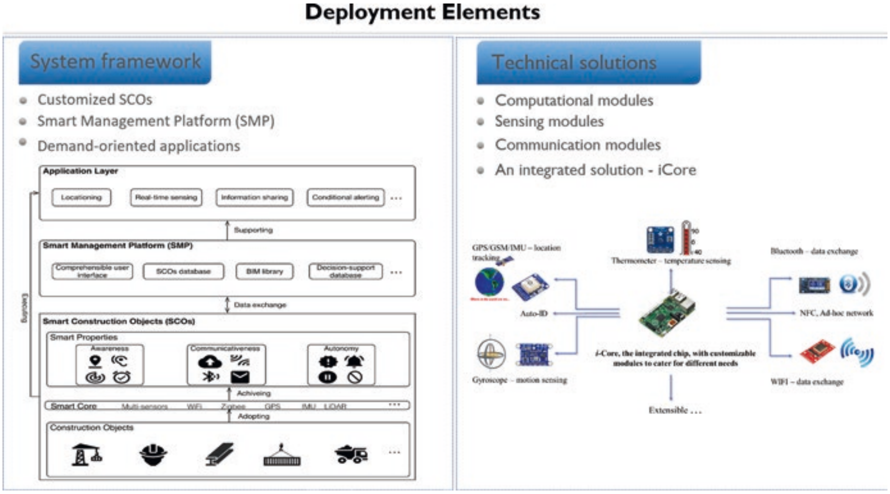

Fig. 15.2 The development of deployment elements of SCOs (Lu et al. 2019)

customizable SCOs, the function units to be included in the smart management platform, and the typical demand-oriented applications of SCOs. It demonstrates how SCOs could interact with people or each other to support construction management by enabling a more connected world of construction. Awareness, communicativeness, and autonomy of SCOs can be achieved by augmenting construction objects with various modules into construction objects, including computing, communication, sensing, and location tracking modules (Liu et al. 2015).

15.3 Cognitive Facility Management

15.3.1 Definition of Cognitive FM

Cognitive facility management (Cognitive FM) is defined as “the active intelligent management of a facility, which can perceive through cognitive systems, learn in the manner of human cognition with the power of cognitive computing, and act actively, adaptively, and efficiently via automated actuators, to improve the quality of people’s life and productivity of core business” (Xu et al. 2019b, c). Cognitive FM proposes to shift the current predicament that a facility is often lagging in serving people, organizations, and businesses smartly (Wang et al. 2018). The tight spot is caused by the passiveness of current FM systems which cannot meet the changing and customized requirements of users in a facility. Most existing FM systems are passive ones with pre-programmed rules, failing to react to complicated, flexible, changing situations. Therefore, FM should and have to be updated with active intelligence mimicking human beings’ cognitive capability (e.g., perception, learning, and action). Cognitive FM is a cyber-physical-social system (CPSS) where cyber (e.g., facility model, computer-aided FM system), physical (e.g., furniture, air conditioning system), and social (e.g., user behavior) information are integrated. The first step for cognitive FM to proactively perceive the requirements of users is to collect user behavior data, with which user preference and requirements can be learned.

The design of cognitive FM is to apply CIoT to FM with the consideration of integrating its cyber, physical, social systems (i.e., CPSS). The aim of Cognitive FM is to enable FM objects to see, hear, and smell the physical world for themselves, make them connected to share the observations, and beyond that, empower FM objects with a ‘brain’ to learn, think, and perceive both physical and social worlds by themselves for high-level intelligence (Wu et al. 2014). Cognitive FM enhances the current FM by mainly integrating the human cognition process into the system design. The advantages are multifold, e.g., achieving situation awareness, increasing self-management, and enhancing service provisioning, to just name a few.

Cognitive FM aims to integrate physical space, cyber space and social space of a facility, as shown in Fig. 15.3. In physical space, there are objects, including all types of facilities and their components, sensing devices like sensors, cameras, smartphones, and actuators, for instance, a piezoelectric actuator, pneumatic

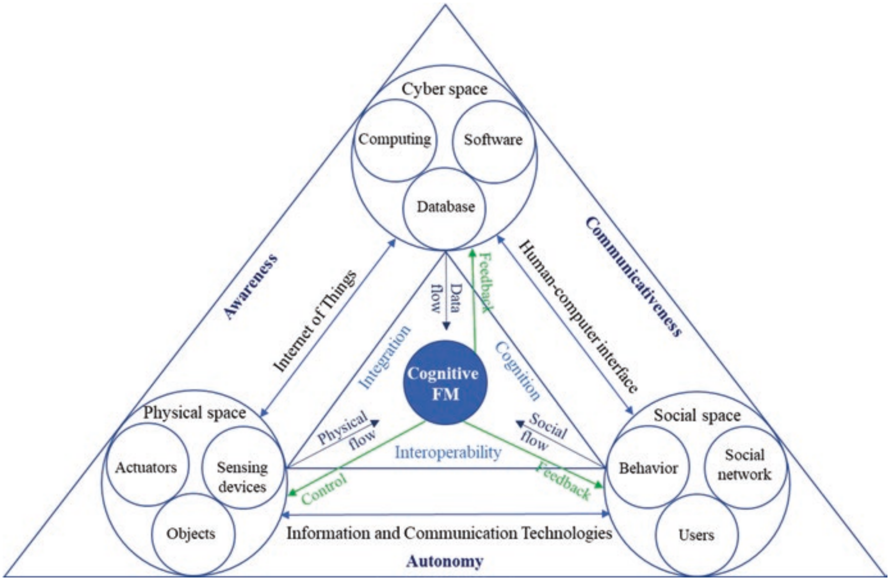

Fig. 15.3 The integration of cyber, physical and social spaces in cognitive FM

actuator, and hydraulic actuator. In cyber space, the major three components are database, computing algorithms, and different software. In social space, users and their behavior, as well as their digital twin, the social media, are the core elements. Physical and cyber spaces are connected with IoT, physical and social, networking, and social and cyber, human-computer interface. Physical flow, data follow and social flow from physical, cyber and social space respectively are integrated into Cognitive FM, which offers integration, interoperability, and cognition through computing. Cognitive FM will also give feedback to the three spaces to control actuators in physical space, update the database and enhance computing in cyber space, and affect user behavior. Finally, Cognitive FM achieves its three main purposes, sharing with the properties of SCOs, i.e., awareness, communicativeness, and autonomy.

15.3.2 Properties and Framework of Cognitive FM

Perception is a primary property of cognitive FM. It is an active process of sensing the internal and external environments. By turning the stimuli from the environment into data, perception provides a system with information about the environment it inhabits (Russell and Norvig 2016). Perception becomes accessible and extendible with the support of cognitive IoT. Sensors/sensor networks, Auto-IDs, cameras, and smart devices and their connected utilities are the 'things' that perceive the internal and external environments of the targeted facilities. Wireless sensor networks

(WSNs) can enable real-time collection of sensory data in different types of facilities (Huang and Mao 2017). Photogrammetry and videogrammetry are extensively utilized for movement and behavioral data collection, as well as the reconstruction of as-is and as-built digital models of facilities. Auto-IDs, including RFID and QR code, are largely adopted in empirical cases for real-time localization, tracking, and navigation (Xue et al. 2018). Smart devices are vital sources of ambient environment and user behavior information.

Learning is another important property of cognitive FM which distinguishes it from others. It consists of cumulating information as memories, acquiring access to the information, and discovering knowledge (Russell and Norvig 2016). In a cognitive system, learning enables object recognition, categorizations, and action execution procedures (Franklin et al. 2014). For example, by learning historic records of indoor temperatures, air conditioning operation, and weather, cognitive FM can realize customized indoor environment control based on occupant preferences, weather forecasting, and other possible factors. Learning is based on observation (watching other's performance and imitating), experience (concluding experiences and recognizing patterns), feedback (reflecting feedbacks and discovering knowledge), and reinforcement (reinforcing by punishment or rewards, respectively) (Illeris 2004). It is a multimodal process in practices with an integration of multiple approaches.

Action is a third property that takes place between the cyber, physical, and social spaces. Simply being in action can facilitate perception and learning. In cognitive FM, actions may include but not limited to statistical analysis and visualization, model reconstruction, alert issuing, option recommendation, decision-making, device actuation, and a combination thereof. Action may execute in three ways, i.e., passively, semi-actively and actively (Casciati et al. 2012). Assisting people with decision-making is the passive action. A typical example would be sensing a notification for facility managers or workers. Semi-active action is the action collaborated by humans and machines. If a facility itself can execute the optimum plan it finds without human aid, then such action is active. A typical example of active action is the auto-control of the lighting system according to occupancy, natural light condition and the function it serves. The accomplishment of semi-active and active action largely relies on cognitive computing and automatic actuating devices.

Figure 15.4 shows the framework of cognitive FM. It has eight layers, i.e., the environment layer, perception layer, data layer, communication layer, computation layer, application layer, action layer, and evaluation layer. The eight-layer framework builds its three properties, i.e., perception, learning, and action, into its structure. It also put the integrating of CPSS into account. The framework can be customized based on different applications. The environment layer is the internal and external environment of the targeted objects. The perception layer should be developed based on data requirements. The data layer is dependent on the application and computing layer. The actuation and evaluation layer should be designed according to available actuating devices and evaluation requirements, respectively. Some technologies or devices may integrate different functions. The several layers of the framework may be integrated but none of them should be neglected in any form.

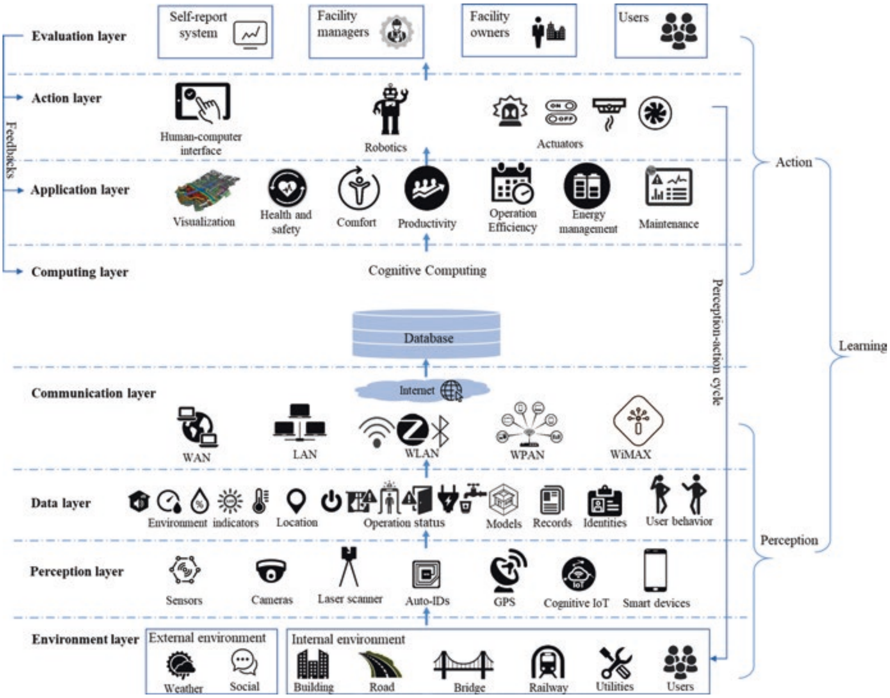

Fig. 15.4 The system architecture of cognitive FM (Xu et al. 2019b)

15.4 The Need to Bridge Smart Construction and Cognitive Facility Management

Section 15.2 introduced the smart construction objects as a paradigm shift and a technical solution for the non-disruptive promotion of smart construction. Section 15.3 proposed a working definition, core properties, and framework for cognitive FM which aims to integrate physical space, cyber space and social space of a facility for proactive intelligence of FM. Although these two pioneering initiatives are far-sighted and share similar insights of integrating the cyber-physical system (CPS) in the built environment, there is a gap between them. They are isolated, only focusing on certain stages rather than the life-cycle of the built environment.

The isolation of construction and FM is an aeipathia in the AECO industry. Due to the complexity of construction projects, different technologies, professional knowledge, experts, and stakeholders are adopted and enrolled, which make their coordination, cooperation, and communication hard and tedious. The common practice is that construction is mainly dominated by contractors under the management of clients, while FM is outsourced to professional FM companies. The gap between contractors and professional FM companies is always so insurmountable that they will lose precious data and information when transferring the project.

Contractors have full records of every construction process and every component but hard to transfer all of them to professional FM companies. While FM companies need those records for better management of the facilities' life-cycle performance. Both academia and industry have long known this problem but cannot bridge the gap with a good approach. The research on smart construction is partitioned into isolated sub-disciplines, mostly too focused on technological tools such as sensors, networking, or automatic control. Meanwhile, there is also a divergent strand of research on FM focusing on the technical part, and just about the same attentions are attracted to the integrated system for FM. But construction and FM are rarely considered together.

It is important and urgent to integrate construction and FM in a loop because of the following four reasons.

Information continuity is the first that would be benefited from construction and FM integration. Data/information is the fuel and enabler of artificial intelligence (AI), cognitive computing, automation, and robotics. The integration of construction and FM will facilitate the continuous flow of information from construction to integration. For example, the production, logistics, and construction information of a beam component can be stored and transferred to the FM system for future monitoring and assessment. A complete record of information is also crucial for decision making. Due to the bounded rationality of human beings (Simon 1972), necessarily integral information will reduce mistakes and save time with better-informed decisions to be made.

Information credibility is another benefit thus can also be achieved when construction and FM are combined. The reliability of information is another dimension that is imperative for decision-making and management efficiency. When facility/asset information can be traced back to the construction stage, credibility can thus be largely improved. With technologies such as Auto-ID, barcode, QR-code, and embedded sensors, information can be recorded and traced back to ensure the authenticity, completeness, and reliability. The blockchain, an emerging information encryption technology, will also help ensure the information credibility from construction to FM. Such technologies have been proved to improve trust and information credibility in the prefabricated component supply chain from production in the factory to logistics during transportation and finally to assembly on-site (Li et al. 2018).

Management continuity is another profit of construction and FM integration. The records of construction management, especially those related to quality management and safety management, are critical for FM. If a construction management system and an FM system share an interface, the management process, management personnel, and management approach can be shared. This is significant, on one hand, for FM, which is able to trace back the management problems should they happen; on the other hand, for construction management, which can learn from FM requirements and feedbacks to better satisfy the operation and maintenance functions. The integration, moreover, will reduce the adding problem of different parallel management systems, decrease duplicated paperwork and confusion between different standards and formats. Furthermore, with sufficient, continued, and reliable information, AI-based management system will be conceivable, such a system will allow less error-prone decisions, autonomous and proactive actions that do not necessarily involve human decision-makers in the loop.

The integration of construction and FM also serves as a pipeline to respond to the call of life-cycle management (LCM), a flexible framework integrated of concepts, techniques, and procedures (Jørgensen 2008). In a facility building project, life-cycle management includes design, construction, operation and maintenance (FM), and decommissioning stages (Labuschagne & Brent 2005), among which construction and FM are the two longest and critical ones. LCM has a focus on both the production site and the product chain. In the built environment, the construction site and production chain from construction to operation should keep as the focus. Construction is the creation of value from design concepts while FM is the realization of value. The value chain flows from construction to FM should not be cut off.

Not only the integration of construction and FM is important according to the four reasons listed above, but also possible with SCO and cognitive FM as initiated. SCO can serve as a hardware foundation and software interface of sensing and computing to achieve awareness, communicativeness, and autonomy. It can be placed in the perception layer in Cognitive FM to collect data for awareness, it can meanwhile serve for the communication layer by its communicativeness, and computing layer with some edge computing capabilities, as well as the actuation layer with its autonomy. Cognitive FM, in turn, will be an integration platform for the implementation of SCOs. With the awareness, communicativeness, and autonomy of SCOs as a backbone, the perception, learning, and action of cognitive FM system will be better achieved. Individual customized SCOs will remain in the facility as smart facility objects and keep functioning as the cells of the cognitive FM. Meanwhile, the cognitive FM platform is the brain of sense-making and decision-making with the continuous information collected from the SCOs. The SCOs at the construction stage are now cognitive FM objects that can perceive their performance and surrounding environment for FM, which does not have to be only taken place after construction but also during it. Supported by the data collected from SCOs and other sensing technologies, the cognitive FM system can better perceive the conditions of the facility, its environment, and its users; learn from the data and patterns; and, provide proactive intelligent actions accordingly. Therefore, SCO and cognitive FM are mutually developed and supported. They should be and can be jointly built up for better integration of smart construction and cognitive FM.

15.5 The Framework of SCO-Enabled Cognitive FM

Cognitive FM aims to develop a CPSS of the FM system. It, therefore, needs to meet the following requirements: (i) human-centric, (ii) decentralized functions and distributed open systems with vague overall system boundaries, (iii) dynamical reconfigured internal structure and reorganized functions/behavior, and changed

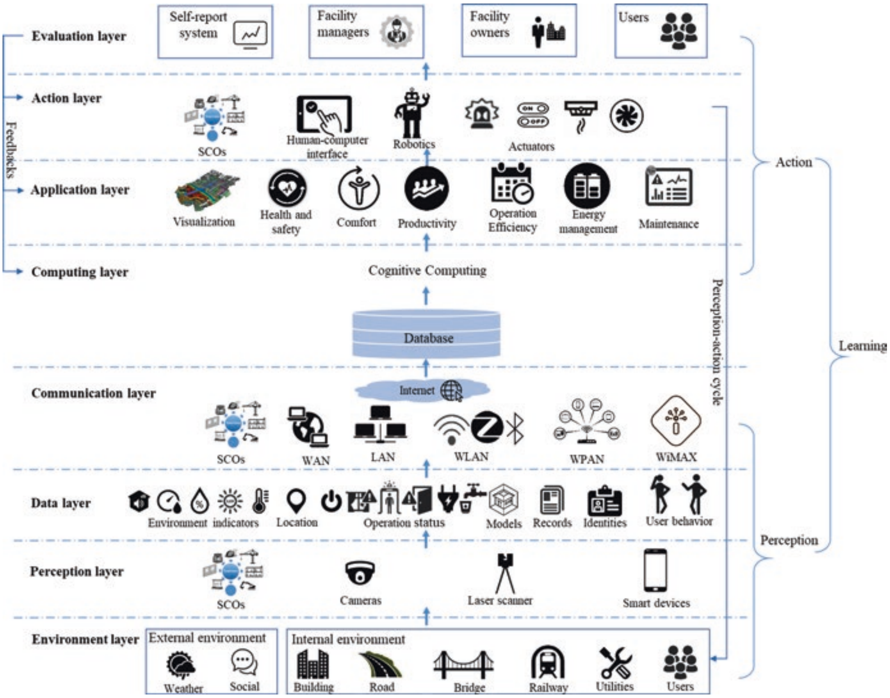

Fig. 15.5 The framework of SCO-enabled cognitive FM

boundaries, (iv) self-organizing, (v) reflexive interactions between system components and multi-constraint optimizations, (vi) real-time operation and communication as well as synchronized manner, (vii) awareness of users and their social contexts, and adaption accordingly, (viii) dependability, accountability, security, accessibility and maintainability, (ix) integration of various percepters and actuators, (x) interoperable components at multiple levels, (xi) knowledge-intensive components, (xii) components that can make situated decisions, (xiii) components that can memorize and learn from history and situations, (xiv) components that can adapt to unpredictable or emergent states and proactively execute non-planned functional interactions, (xv) large volume of heterogeneous data from cyber, physical and social worlds, complex and dynamic user behavioral patterns (Horvath 2012; Kuang et al. 2015).

An SCO-enabled cognitive FM will meet these requirements by adopting SCOs across different layers, as shown in Fig. 15.5. SCOs will act as important components in the perception layer, communication layer, and actuation layer in the eight-layer framework. Each of the eight layers has their own functions and characteristics:

1. The environment layer consists of the internal and external environments of a facility. The external environment, including natural and social components,

forms the context which the facility is positioned in and exposed to. The facility as a whole is the object of cognitive FM, therefore its internal environment is the utilities and users within the facility. It is the layer where all commercial, residential, and social activities take place, and also the layer the system needs to perceive through sensing technologies. All the objects can be augmented by sensing, communication, and computation technologies to become smart objects.

2. The perception layer entails SCOs and other devices that operate in a connected fashion to capture the features of the environment layer. SCOs as an integration of different sensors can sense the environment by processing the incoming stimuli and feeding observations to the upper layer (Jung et al. 2019). They can detect the status or characteristics of different objects. The information collected by SCOs is interpreted by the cognitive computing behind.
3. The data layer contents various data types generated after perception, including environmental indicators, such as temperature, humidity, luminosity, air pressure, or particulate matter density. It may also comprise pictures, video or 3D point cloud data of a facility or area, the identities of building components, furniture and users, locations, operation status, user behaviors, and other characteristics.
4. The communication layer is in charge of uploading the sensing data to the database, mimicking the nerve system of human beings. There are various communication protocols available. Facility managers should choose the appropriate protocol based on their requirements and budget. Local and wireless communication protocols (i.e., LAN, WAN, and WLAN) are widely used in various current applications (Tolman et al. 2009). Personal networks (e.g., WPAN) and interoperable networks (e.g., WiMAX) are emerging and likely to popularize in online social communication. SCOs can also serve as a communication medium by integrating communication components such as Bluetooth, WiFi, or NFC.
5. The computation layer is responsible for analyzing the data collected from the lower layers to support decision-making by harnessing the power of cognitive computing. SCOs with a computing board are also capable of doing some edge computing works and communicate the preliminary results to the cognitive computing system for further computation.
6. The application layer makes use of the knowledge abstracted from the computation layer to facilitate multiple or even massive interactive agents (e.g., facilities or users) to support corresponding smart construction and cognitive FM applications.
7. The action layer takes the decisions into actions by controlling the objects and changing the perceptron via the human-machine interface, robotics, or actuators. SCOs have the capability of issuing alerts or guidance that can also act as actuators from this aspect. Robots with caring, operation or maintenance abilities are also intelligent actuators with a promising future in cognitive FM.

8. The evaluation layer is for the evaluation from stakeholders. It can share import interfaces with social network software for wider evaluation collection. Performance questionnaires will be designed to rate the services provided. More importantly, the evaluation results will serve as feedbacks to the application layer to improve application objectives and variables, or to the comutation layer to upgrade the learning algorithms, even to the perception layer to better customize SCOs and other devices for better perceptions.

As described, SCO can fit perfectly in the cognitive FM framework and work as an enabler by playing multiple roles across different layers. The SCOs in the form of construction components, machinery, and devices should be preserved, if necessary, for later operation and maintenance. To encapsulate these modules in an integrated manner, a standalone, programmable, extendable integrated electronic chip, named i-Core, is developed as one of the technical solutions (Lu et al. 2016). Able to be implanted into machinery, devices, and materials, and similar to a computer central processing unit (CPU), the i-Core turns deadweight construction components and plants into SCOs and makes smart construction possible. Implementation of the three core SCO properties relies on the integration of various computing, sensing, and communicating modules into the i-Core. To meet the changing needs of construction sites and achieve different functions, these modules are extensible and can be selected and customized case by case.

For example, a smart beam component object attached with an integrated chip (i-Core) or an Auto-ID, manufactured either off-site or on-site, is a smart construction object at the construction stage and will keep as a cognitive FM object when the facility is finished and put in use. The data collected and stored from the construction stage can be kept and new data perceived during the operation stage will be added to construct a life-cycle dynamic dataset of the beam component. With many interconnected and intercommunicated objects turned into smart ones during the construction stage, the facility itself is a cognitive one which can perceive its internal and external environment, learn from historic data, and act proactively to meet customized and changing requirements of users and support the decision-making and management of facility managers in the changing environment.

15.6 Proposed Scenarios of SCO-Enabled Cognitive FM

To better illustrate how SCO can enable cognitive FM, two scenarios, proactive structure assessment, and life-cycle MEP system monitoring will be proposed and explained.

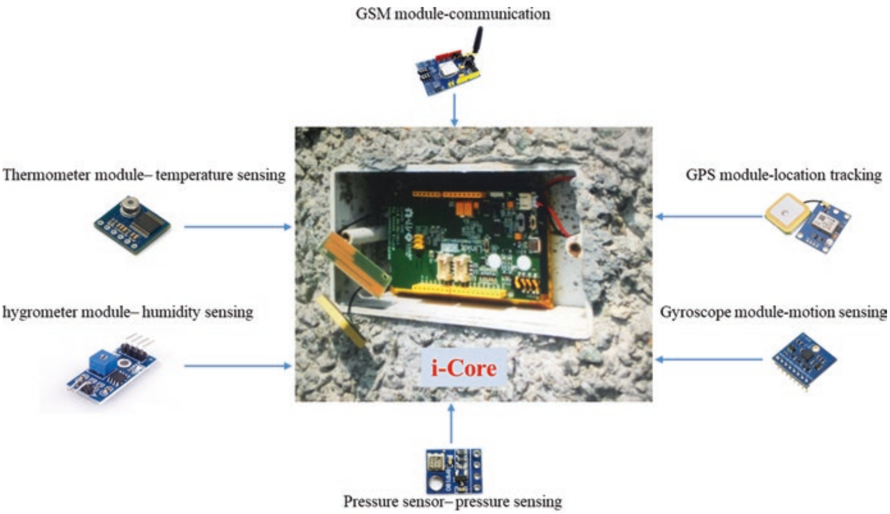

Fig. 15.6 The customized i-Core design for smart prefabricated beam object

15.6.1 Proactive Structure Assessment

In this specific scenario, prefabricated beams will be turned into SCOs augmented by i-Core, not only to facilitate logistics and supply chain management in the construction stage but also to support proactive structure assessment during operation and maintenance stage. The customized i-Core in this scenario integrates an Arduino chip with GPS and GSM module, sensor network, and Auto-ID together (see Fig. 15.6). GPS module enables the tracking of the beam. A customized sensor network with a gyroscope, thermometer, hygrometer, and pressure sensor will enable the perception of the internal and external environment. Auto-ID can store information such as manufacturing date, concrete and steel parameters, quality checking records, etc. A small smart chip with the ability of simple computing and communication will proactively send messages or report status of the location, transportation speed, and environment indicator records based on pre-set rules. The framework of the proactive structure assessment system is shown in Fig. 15.7.

During the construction stage, it can support logistics and supply chain management (LSCM) via the cognitive FM platform. Augmented by the tracking and communication modules, real-time bi-directional information flow between SCOs and the platform (forming a CPS) will be achieved, along with concurrent information and material flow during the LSCM process (Niu et al. 2016b). Such a CPS will facilitate the real-time location checking of the prefabricated beam. The site manager can predict the arrival time of the truck and arrange transportation into the site. He/she can also plan for the temporary storage area or hoisting tower crane for the coming prefabricated beam. Once the beam arrived at the site, with a scanning of the Auto-ID, a receipt will be automatically issued to the manufacturer. To

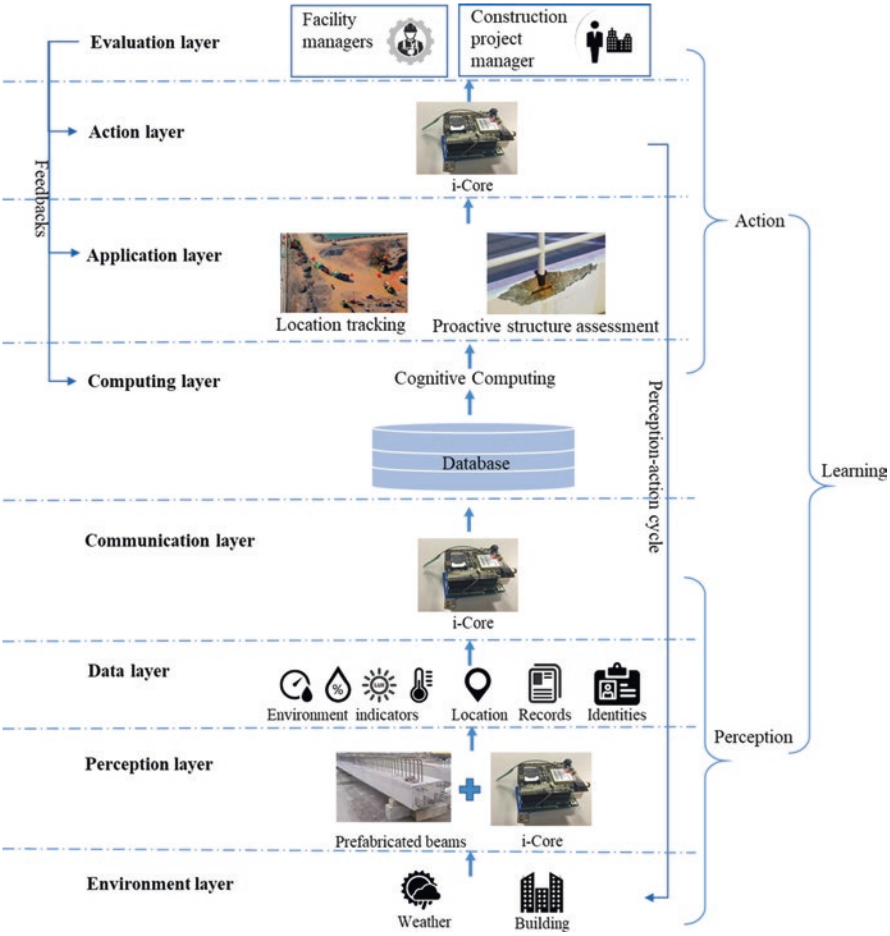

Fig. 15.7 The framework of SCO-enabled proactive structure assessment

conclude, better and informed decision-making of material arrangement, labor and machinery planning, and construction progress management with less time lagging will thus be ensured for the procurement manager, material officer, and project manager.

When the construction is finished, the i-Core embedded in the prefabricated beam object can be used for proactive structure assessment during the operation and maintenance stage. The framework of SCO (i.e., the smart prefabricated beam object) enabled cognitive FM is illustrated in Fig. 15.7. With the sensor networks, the environment indicators including temperature and humidity, and the pressure loading on the beam can be collected. Auto-ID will store the identity of different components including beams, columns, plates. Such records stored in the database together will provide a foundation for proactive structure assessment. With cognitive computing, when the temperature, humidity, and other supporting indicators, are out of the normal ranges, alerts will be automatically sent to facility managers, asking them to check the status of the beam to see if there are abnormal situation happening to the beam. Also, when the loading pressure onto the beam is beyond the normal range, messages will be sent to the facility managers for a closer check. Moreover, such alerts and notifications are sent via the cognitive FM platform where it will keep a record of them and issue work assignments accordingly to maintenance stuff. The structure assessment is thus turned from passive by manpower to proactive self-report by the objects which are already augmented with smartness at the construction stage.

In this scenario, i-Core endowed SCO, the smart prefabricated beam component, is functioning as the integration of perception layer, communication layer, and actuation layer of cognitive FM. With other similar SCOs such as columns, plates, doors, windows, and other components all transferring to the FM stage, the facility per se is a network of smart objects, which lays a solid hardware foundation and software preparation for cognitive FM. By making use of the embedded technologies in the SCOs, the cognitive FM platform will cumulate rich big data for the nurturing of proactive intelligence. Such intelligence will not only serve for better physical facility management, but also better services provided for users and their customized needs.

15.6.2 MEP Auto-Monitoring

The second scenario illustrated is the MEP (mechanical, engineering, and plumping) monitoring. The MEP system is the kernel of modern facilities, especially for various types of buildings. However, due to its complexity and elusiveness, it is difficult to monitoring. Currently, it requires professional workers to check the components one by one. When partial failure happens, it is difficult to locate the part need to be fixed. An overall replacing to the whole system will be adapted during updating and renovation. All the current practices are quite tedious, error-prone, and expensive. SCO-enabled cognitive FM system may be a possible approach to relieve facility managers from their previous tedious routine work and save monitoring costs. The framework of SCO-enabled automatic MEP monitoring is displayed in Fig. 15.8. The MEP objects are augmented with smartness by attaching sensor networks at the construction stage when contractors are installing the MEP system.

According to Fig. 15.8, the MEP system is the major internal environment the cognitive FM investigates in this scenario. Sensor networks, be they wired or wireless, are attached to MEP systems and concealed by plates or walls at the construction stage. The sensor networks can be customized according to the monitoring requirements. Basically, thermometers, hygrometers, pressure sensors, sound sensors, and voltage sensors will be needed. Together they will be able to collect temperature, humidity, pressure, sound, and voltage of the MEP objects automatically. The sensing data thus will be uploaded to the database via LAN or WLAN. Cognitive

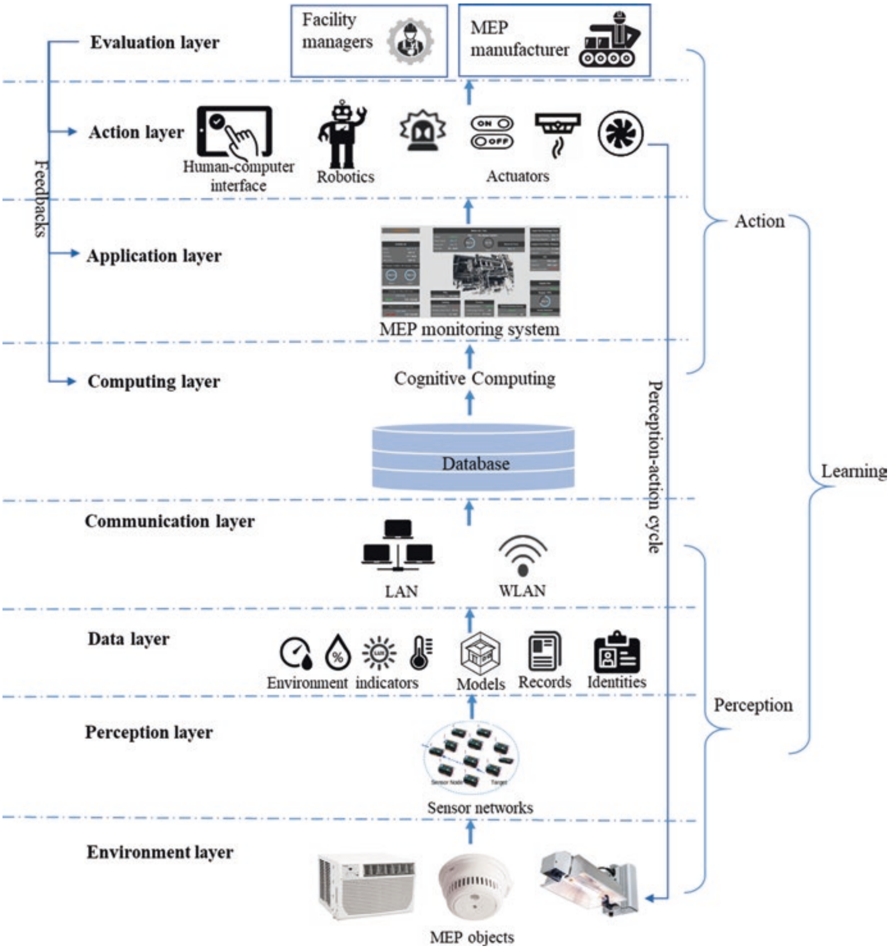

Fig. 15.8 The framework of SCO-enabled MEP auto-monitoring

computing modules will extract data from the databased for automatic analysis and monitoring. If cognitive computing of the temperature, humidity, pressure, sound, and voltage data detects any anomalies, notifications will be automatically sent to facility managers via the human-computer interface of the cognitive FM platform. The sensors are identified with numbers and located in a digital model, thus the notification of anomaly will be tagged with identification and location information. Therefore, FM staff can quickly find the failed object and fix it. Robotics can even be sent to fix the problems if possible. It is necessary when an emergency happens, or it is unsafe for workers to access. Under situations where residents need to be evacuated, alerts will be triggered, and messages will be sent to them via platform-to-person interface. For some other situations where actuations of the MEP system are needed, automatic control, e.g., turning on/off the power, resetting working temperature, opening fire-fighting system, can also be taken as responses. With the power of cognitive computing, the anomaly reasons can also be identified to support predictive maintenance. Facility managers can, therefore, plan the monitoring and maintenance to the point and avoid large scale failures. More importantly, the statistics of anomaly reasons and details can be reported to MEP manufacturers for their updating and optimizing the MEP objects from the design and manufacturing stage.

In this MEP auto-monitoring scenario, MEP objects (e.g., air conditioner, fire alarm, lighting devices) are turned into SCOs during the construction stage by embedding sensor networks, but their bigger value is showing in the FM stage. By proactively collecting operation data through sensor networks, auto-monitoring of the MEP system is facilitated. It can meanwhile support emergency management, evacuation management, environment management, and energy management of cognitive FM. Passive monitoring by FM staff is replaced by proactive reporting with smart objects. Such a cognitive FM scenario will not only simplify the process of MEP monitoring, but also relieve FM staff from tedious and dangerous works. Therefore, the efficiency of FM will be improved, and the cost of monitoring will be reduced as well.

15.7 Discussions

The previous sections have introduced the SCO, cognitive FM, the framework and scenarios of SCO-enabled cognitive FM. The initiative is promising and feasible in the coming smart era. However, there are also some challenges ahead that should be discussed, including but not limited to power supply for SCOs, cost, data integration, and data storage.

Technically, the operability of the SCOs needs to be improved. Although pervasive sensing technologies are becoming increasingly accessible, one burning technical issue is the continuous power supply of the sensors. When the SCOs will be kept in the facility and operate for a long time, their power supply is a big and direct problem. Currently, some sensors/sensor networks rely on batteries for power, however, constrained by the duration of the batteries, they can only survive for days or months but incapable of working for a long period of time. Alternative methods offer rechargeable batteries or charging modules for continuous power supply. However, the wiring, switching, and protection of such a complex system are also burdensome. Therefore, a better and smarter power supply for sensors/sensor networks is a tough problem to be overcome.

Economically, the cost is always the biggest concern. Although the prices of hardware such as sensors and integrated chips are declining quickly, the development of a platform that bridging the hardware and software is still relatively expensive. Besides, the cost of applying cognitive computing in such a platform is rather high. Patience should be paid for the maturing of algorithms and computing ability. The cost of adopting a new solution is, on the other hand, mainly contributed by managerial aspects. The training of new technicians, the changing of the organization, and the development of the new regulations at the initial stage will cost a lot of money. However, since the smart era is an irresistible trend, the upgrading of construction and FM is a must. From a long-term aspect, the investment at the initial stage can be compensated at later stages. The money will be saved by fewer manpower requirements, less routine and tedious works, less management expense, fewer errors, less repeated work, higher efficiency, more time saved, and better service provisioning. In summary, the benefits will offset the cost in the long-term.

The integration of data among different protocols is also a challenging issue facing by most attempts of CPS development including those in the built environment. Different sensors produce data with different formats, and different systems have different data requirements. The integration of data from different sources among different systems will inevitably cause the missing and garble of data. To share and communicate data among different hardware and software, a unified data protocol that is compatible is required. A unified data protocol is not only the gateway towards cognitive FM in the built environment, but also towards any IoT-enabled systems in the smart era.

With a large amount of heterogeneous data collected and cumulated, data storage is another issue with tremendous attention. Although the data storage capacity is increasing day by day, the accumulation of data increases even faster. Moreover, to avoid physical damage or failure of storage hardware, data backup is necessary but expensive. The cloud storage might be a feasible alternative but arguably because of being unsafe from attack and leakage. Consequently, a cheaper and safer data storage scheme is a non-trivial problem that should be seriously considered and discussed.

15.8 Conclusions and Future Work

This chapter proposed a new concept, together with a new framework, of SCO-enabled cognitive FM under the umbrella of the cyber-physical system (CPS) in the built environment. Based on two creative and futuristic concepts, smart construction object (SCO) and cognitive facility management (Cognitive FM) proposed by the authors, we take this chance to take a step further to integrate them for a bigger blueprint for the architecture, engineering, construction, and facility management (AEC/FM) industry. By integrating the two concepts, this initiative aims to enhance information continuity and credibility, management continuity, and life-cycle management in AEC/FM for better-informed decision-making and smarter services provisioning. The definitions, properties/key elements and framework/system architecture of SCO and cognitive FM are thus reviewed separately. After discussing the necessity and feasibility of integrating the two concepts, a framework of how they will be integrated is proposed. SCOs as the integration of sensing, communication, computing, and actuation technologies can work as smart objects during the operation and maintenance stage across different layers in the cognitive FM system architecture. SCOs are thus enablers of cognitive FM. To better illustrate the function of SCOs and their implementation in cognitive FM, two scenarios, i.e., proactive structure assessment, and MEP auto-monitoring, are briefly described.

Based on the discussion of challenges, there are plenty of works to be done in the future. Technically, in the meantime of developing higher performance sensors at cheaper prices, the power supply of the sensors should be paid more attention. A stable and durable power supply is the bottleneck of widespread SCO adoption and other IoT-related development. The integration of heterogeneous data is another burning issue, as well as the safe storage of increasing big data collected from different sensors and systems. Data, as the fuel of AI and robotics, is the fortune that should be carefully stored, protected, and utilized. On the economic aspect, empirical cases should be piloted and studied for a detailed cost-benefit analysis of the SCO-enabled cognitive FM. From the management perspective, how such an SCO-enabled cognitive FM system should be designed, organized, and managed is a primary issue to be attended to. Although there are a lot of future works to do, it is believed that SCO-enabled cognitive FM is a paradigm shift in the AEC/FM industry and will be accomplished in the near future.

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Chapter 16
Cyber-Physical Social Systems for Facility Management

Saratu Terreno, Abiola Akanmu, Chimay J. Anumba, and Johnson Olayiwola

16.1 Introduction

The term ‘Facilities management’ encompasses a series of processes involved in maintaining, improving and adapting buildings of an organization to the needs of the users (Barrett and Baldry 2009). The success of the facilities management process is hinged on how well the concerns and feedback of the facility users/occupants can be captured and addressed (Becerik-Gerber et al. 2011). Some of the most common concerns of facility users include the rising cost of energy (Lewis et al. 2010), occupant’s dissatisfaction with the condition of building spaces (Han et al. 2012), time taken to manage work orders and delayed detection of non-functional building systems. To address these concerns, it is important to devise mechanisms for effectively capturing and evaluating the interaction between the users and the facilities.

It is increasingly being recognized that improvements can be made to facilities management addressed by effectively monitoring and coordinating the management processes. Monitoring and coordination requires real-time functionalities, which can be achieved through the tight integration of virtual resources and the physical facility using technologies and networks – this is termed cyber-physical systems (CPS) approach (Sutrisna et al., 2015). However, to date, there have been limited CPS based studies in facility management. These studies have been largely focused

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on the complexity of engineering elements, ignoring the social aspect. The traditional CPSs do not quantitatively estimate the impacts of humans and the facility management organization, which can be uncertain, diverse, and complex. In other words, the significance of human operators as part of physical systems is not being addressed as part of CPS (Lee and Seshia 2011). Excluding the human factor means that traditional CPS may not adapt to all facility management business situations. With time, such systems may become useless under some conditions. These human-centered behaviors can be captured, analyzed, and employed in controlling and managing the performance of facilities using computational tools and techniques. In recent years, to improve the interaction between the physical systems and users, a concept of cyber-physical social systems has been proposed. Researchers (Guo et al. 2015, Smirnov et al. 2015, Yang et al. 2018) have defined CPSS as a complex system that consists of a physical system, and its social system including human beings, and the cyber system that connects them. By explicitly incorporating facility users and managers into CPS, facility management will offer new opportunities for effective sensing and control of building systems.

Hence, this chapter describes a framework for incorporating cyber-physical social systems in the facility management process. The framework includes the context and challenges with the existing facility management process. The need for transitioning from traditional facility management to CPS is discussed. The chapter also describes the cyber-physical social systems process, system architecture, and processed some potential applications.

16.2 Physical Facility System/Management

Constructed facilities consist of components and systems assembled to shelter and meet the comfort needs of the users/occupants. These systems include the mechanical, electrical and plumbing systems, and the building envelop system. Managing these facilities involves maintaining the structural and physical conditions to meet its intended purpose. If effectively executed, facility management could promote productivity, safety, and comfort of employees and building occupants. Most organization facility management departments are responsible for the planning, design, construction, operation, maintenance, and renovation of their facilities. By interpreting and acting on the data in real-time, fixing maintenance issues, and saving energy when a building is unoccupied; ultimately reducing costs. Facility managers need to be constantly up-to-date on the status of their buildings at all times, and be able to see, understand and fix the building problems. Daily, facility managers ensure that components and systems in buildings run efficiently. These systems often require different levels of periodic intervention to run optimally. This raises several challenges ranging from simple daily interventions to complex solutions that involve multiple parties. One of the keys to handling these issues involves identifying the potential problems early so as to have ample time to devise the most efficient and effective resolution strategies.

16.3 Facility Management Social System

The emergence of social media, social application, and social network sites have provided platforms for people to connect, share thoughts, ideas, and concerns, and obtain useful information. Building occupants and users directly or indirectly provide information critical for improving the management of facilities. Such information includes reviews of leased and rented apartments, occupancy of spaces, defects, pictures and video images of buildings. There are a number of machine learning algorithms and tools like Buffer, TweetDeck (Geho and Dangelo 2012, Carscaddon and Chapman 2013), Social Booster or Hootsuite (Sump-Crethar 2012) that enable keywords, geo-location tags, and specific users or occupants to be digitally observed and followed. By observing social media systems, facility managers can capture trends in comments that might trigger or require physical, environmental and security changes within their facilities. For example, if a number of occupants or users tweet about the condition of a space, office or room that they are too cold or hot, a facility manager could quickly act before receiving any formal complaints. This is usually a key concern for individuals who work or occupy shared spaces. While facility managers will not be able to satisfy each occupant's comfort needs, social media systems could enable the identification of patterns that should clarify whether complaints are of an individual concern or comprehensive in nature.

Facility management social system has an influence over decisions and behaviors of individuals, building occupants, facility owners, and the management team. Facility management social system captures, integrates and spreads facility-related information and resources from multiple sources effectively. Figure 16.1 shows an architecture of a facility management social system.

The public can release or acquire on-demand facility-related information and facility managers and owners can improve their management practices and design

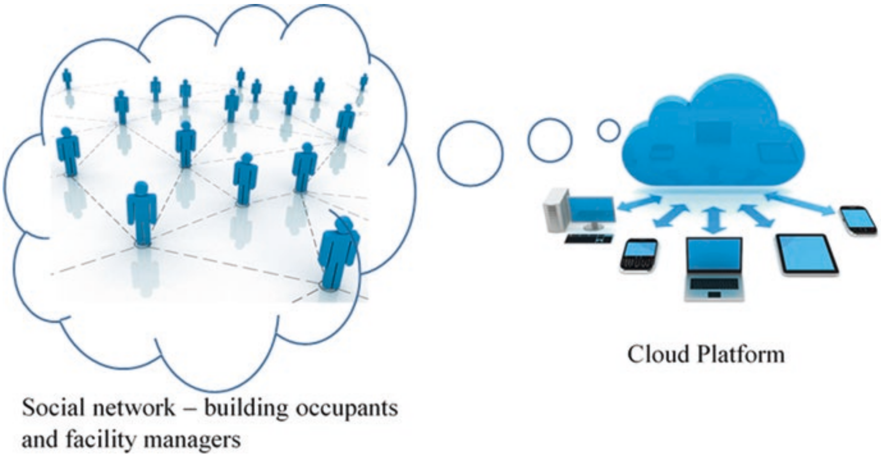

Fig. 16.1 Facility management social system

decisions. Facility management social system can be deployed and structured on the cloud platform, so that the public and related organizations can partake in the sharing and access using the internet. Some of the information that can be extracted from a facility management social system includes: building defects, faulty building components, building use, space congestion, livable spaces, and thermal comfort. This information can be extracted, sorted or inferred from an individual's social networks or organization's review sites. Furthermore, facility management social system can also be considered as a social sensor network. Facility management departments and building owners can use the sensor network to capture social building defects, occupant concerns, space utilization and emergency events, which can support related decision making and improve the service level of facility owners. Such a facility management social network will require emerging computing techniques and technologies, such as mobile internet, cloud computing, and big data. Organizations with well-established facility management departments (e.g. educational institutions and rental agencies) currently implement facility management social systems.

16.4 Cyber-Physical Social Systems

The facility management process is a typical candidate for CPSS. CPSS-based facility management relates the physical facility systems to the social elements. The elements of the physical facility system include the physical buildings and components, systems (e.g. mechanical, electrical and plumbing systems). The elements of the facility management social system include owners, facility managers, building occupants, culture, climate, and environment. It has dynamic, open, interactive and autonomic features. With the aid of innovative technologies and techniques, CPSS can be achieved by tightly integrating physical facility systems with facility management social systems, as shown in Fig. 16.2.

16.4.1 Architecture and Supporting Technologies of Cyber-Physical Social Systems

A CPSS is a complex system consisting of a physical system and its corresponding social system which includes human beings, both integrated with a cyber-system. CPSSs typically rely on communication, computation and control elements/infrastructures for operation. These infrastructures include sensors, actuators, computational resources, services, and humans. Figure 16.3 presents a four-layered architecture of the CPSS-based facility management. The architecture comprises of the sensing, processing, data fusion, and applications layers. These are described as follows:

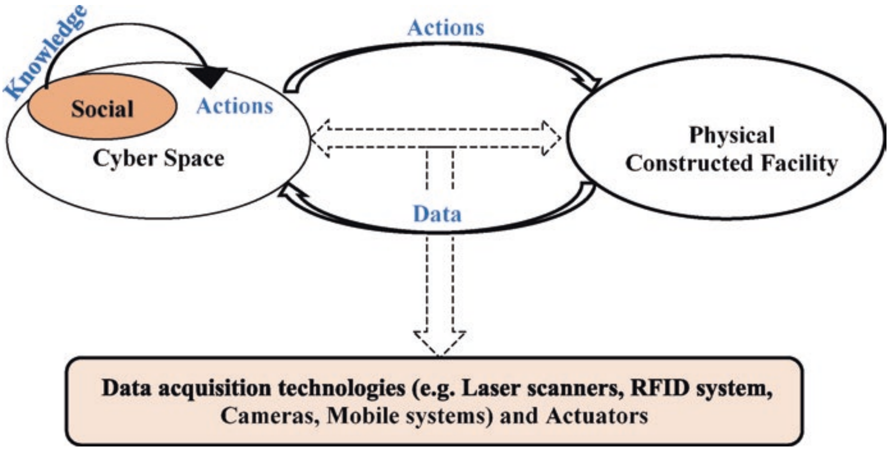

Fig. 16.2 CPSS system architecture

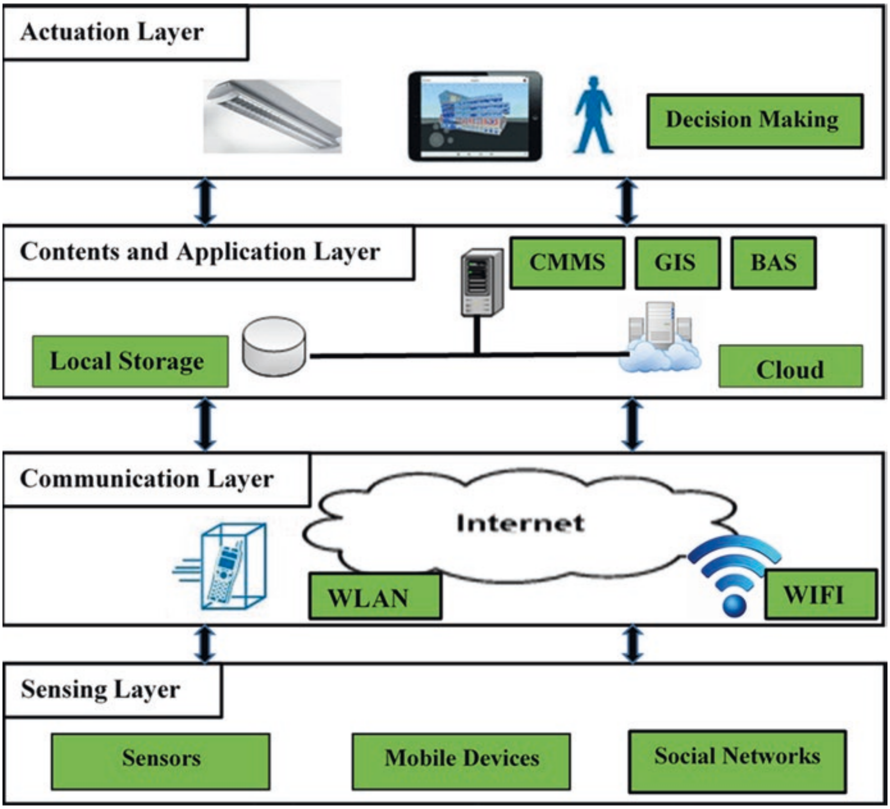

Fig. 16.3 A conceptual framework for CPSS-based facility management

16.4.1.1 Sensing Layer

The data sources in a typical CPSS-based facility management system includes sensing technologies, mobile devices and social networks. The sensors which includes component and image-based sensing systems capture near or real-time information about the building systems, components or spaces. Depending on the application, the sensors also capture the movement or context of building occupants and the maintenance crew. Data acquisition technologies such as smartphones and mobile tablets can be used by building occupants to share their thoughts and opinions about the condition of the buildings. The data acquisition technologies can also be used for conveying explicit knowledge (e.g., by occupants or users uploading building-related data from the sensor inbuilt in their smartphones) as well as passively (e.g., users contributing or providing opinions and thoughts to social networks, that can then be analyzed for building maintenance).

16.4.1.2 Communication Layer

The communication layer serves as the data processing and communication unit. This layer pre-processes data obtained from the sensing layer by converting to formats readable by the contents and application layer. This layer contains data processing algorithms as well as analytics techniques that are applied to the data obtained from the sensing layer. The layer also includes all the required preprocessing steps such as removing noisy instances, filtering, and pre-sorting of data. Data processing usually involves clustering and classification of corroborative information e.g. structuring image or global positioning system (GPS) data referring the same or close locations, from social media. Data from maintenance personnel can also be clustered according to the category or type of building component or systems. The physical facility space and social data can be processed to derive relevant patterns and abstractions, which can be utilized by the data fusion to derive knowledge. The communication layer also contains the internet and wireless communication networks e.g. wide area networks and local area networks. These communication networks also connect the sensor and data acquisition technologies to allow for accessing social media sites, networking and information sharing.

16.4.1.3 Contents and Application Layer

The contents and application layer contain the database server and control applications such as Building Automation System, Computerized Maintenance Management System (CMMS), Building Information Model (BIM) and Geographic Information System (GIS). This layer also contains cloud computing platforms such as Microsoft Azure, Amazon Web Services and Google Cloud Platform, which are third party internet paradigms that provide access to shared pools of configurable resources (Bughin et al. 2010, Zhang et al. 2012). These computing platforms provide opportunities for capturing and storing data from multiple users, while also rendering other services such as data analytics and integration. A number of industry sections outsource their data storage and computation to these platforms. Cloud computing has been widely proposed and explored in the AEC research for real-time collaboration of project teams from design to construction phase (Porwal and Hewage 2013), the capturing and storing sensor data (Hong et al. 2012, Fang et al. 2016), integrating project management data with building models (Jiao et al. 2013), design and structural analysis applications (Klinc et al. 2014), and for advancing e-procurement in the construction industry (Grilo and Jardim-Goncalves 2013). The control applications use the sensed data from the database to make control decisions that can be visualized using the virtual prototype interface in the actuation layer. This layer also contains various statistical or logic-based methods to integrate the outputs from the communication layer in order to achieve information in actionable or decision-making formats. This layer stores, analyses and is constantly updated with information collected from both the communication and actuation layers.

16.4.1.4 Actuation Layer

This layer obtains the processed information or decisions from the contents and applications layer and presents it in actionable formats. The required actions could be a passive or active control. Depending on the type of control needed, the actuation layer could provide access to critical information needed for decision making or physically control the physical environment using actuators. The passive control could be in the form of human actions and decision making. Information required for decision making could involve the Identification of equipment, geo-location of faulty equipment, type and nature of repair required. Active control might involve automated control of building components. The actuation layer contains the virtual prototype which is accessed through the user interface or a mixed reality environment. The virtual prototype enables the user to visualize how the sensed information (from the contents and storage layer) affects the system. The user interface enables the user to visualize and monitor the sensed information from the contents and storage layer. The user can also embed control decisions into the virtual prototype through the user-interface to be accessed in the device layer.

16.4.2 CPSS-Based Facility Management

To achieve a CPSS-based facility management, the physical facility system needs to be merged with the facility management social system by including the human and social dimensions into CPS. The cyber system thereby changes the way humans interact with facilities and each other. CPSS-based facility management promises scenarios where a physical facility runs interactively with the social space through the cyber space. This type of close-knit system could aid the following: façade maintenance, component malfunction detection, and design for maintainability practices for new buildings. These are described below:

16.4.2.1 Scenario 1: Façade Inspection

The periodic inspection of building facades is an important requirement for preventing damage to the core of facilities. In high-rise buildings, the safety of the maintenance personnel is a significant concern; and in large property holdings such as on a university campus, time is another important consideration. The use of an Unmanned Aerial Vehicle (UAV) would serve to address these concerns, as the remotely controlled device enables remote and speedy access to all angles of a structure when fitted with a live feed camera for added visualization capabilities. On the other hand, in disaster-prone areas, regular inspection is important to determine residual defects that linger post-disaster. These warning signs may be missed if inspection is scheduled periodically. Building image data (such as images and videos) uploaded on social media by building users or passersby, can also inform facility managers of the conditions of building facades. These images could be complemented with those obtained from the UAV for detailed damage classification and analysis. The use of CPSS to facilitate façade inspections has the potential for early detection of warnings, significantly reduce time and safety concerns, and is described below:

1. A UAV fitted with a GPS tracker is mounted with a camera and deployed to fly around the geographical area of interest. The location of the UAV is tracked by GPS linked with the coordinates of the virtual model. The flight path of the UAV is displayed in the virtual model. The camera transmits live video feeds to the remote inspection team.
2. The team directs the UAV by remote control to view the building from different angles as required. When a condition of interest is found, the team uses the camera to take still pictures. Simultaneously, there is a close mapping/binding between the physical buildings on the campus and their digital representations in the virtual model. This locates the coordinates of the still image – vertical and horizontal- and based on established survey points within the 3D model's coordinate system. When a condition of interest is found in an image, the image will be stored in a database.
3. Likewise, geo-tagged images and videos related to the building façade that are available on social media are collected. Machine learning and real-time data mining are leveraged for identifying any significant or troubling patterns from social media data.
4. The images (from the UAV and social media) are sent back and attached to the BIM model of the facility, which in turn updates the facility's CMMS and issues a notification of an inspection observation. The BIM model can be used to visualize the building and materials, and the GIS map can be color-coded to illustrate building maintenance needs, based on previously established parameters. The

CMMS is linked to related documentation (insurance documentation, warranties, building codes, etc.). The facility managers are notified when images with a condition of interest are identified. This will suggest a physical inspection of the area of the building.
5. The integrated information in the CMMS is bound to the BIM model and GIS through hyperlinks and is sent to the iPad or smartphone of the Maintenance Manager, who analyzes the façade issues.
6. The Maintenance Manager, following assessment of the level of criticality of the defect, sends the information to the iPad or smartphones of the field team concerned with the repair if it requires urgent action. In the event that it can be addressed at a later date, he/she writes the information to the sensors/tags associated with the defective façade, to be recorded as part of its maintenance history and to be addressed at a later date during routine inspection.

This scenario illustrates the two-way coordination of information and control back and forth between the remotely located inspection team, and their device of choice, the UAV and the social media.

16.4.2.2 Scenario 2: Coordination of Building Temperature

In public buildings (such as institutions and companies) and shared spaces, occupants respond differently to set-temperature. If the room temperature is unsatisfactory, building occupants tend to be uncomfortable and this affects their performance. Nearly, two-thirds of American adults use social networking sites (Gomathi and Gowtham 2013). People use social media to maintain relationships, interact and collaborate by “sharing,” “liking,” and “retweets”. The application of CPSS for controlling building temperature is described below:

1. Multiple building occupants in a shared space individually tweet that their room is too cold.
2. This information is captured from social media using real-time streaming. Machine learning algorithms are used to structure and identify trends from the captured information. Although facility managers cannot meet each building occupant’s comfort needs, social media data could enable trends or patterns to emerge that will illustrate whether complaints are of an individual concern or comprehensive in nature.

The facility manager uses the BAS to make adjustments before receiving any formal complaints from the building occupants.

16.4.2.3 Scenario 3: Response to Emergency Situations

There is a global surge in active shooter incidents in the United States (Cruikshank 2017). These incidents have extremely negative effects, including loss of life, triggering fears among citizens and impeding strategic plans of first responders

(Sweeney 2019). In buildings or other constrained spaces, active shooter incidents evolve quickly. Although people are sometimes trained to run, hide and fight before the arrival of first responders, psychological stress is inevitable. People will process the shooting in different ways, and the nervous system response will kick in and possibly override any training received. CPSS addresses these problem as follows:

1. In the midst of the chaos, some building occupants tweet pictures and videos via social media.
2. A machine learning algorithm is developed to search posts on social media relating to active shooter incidents. The location of the building is determined via the geo-tags of social media posts. These social media data could inform how building occupants are responding to the situation, where they cluster, congested evacuation routes and individuals with disabilities – having difficulty evacuating via main routes and the location of the suspect.
3. The algorithm is linked with the BIM model of the building. The facility managers receive an alert to check the location of the incident.
4. From the BIM model, the facility manager can determine the nearest and safest exits for the occupants of the building. Also, the whereabouts of the shooter can be determined and the information communicated to public safety officials. Serious safety events and security breaches can be reported early. This real-time information would be critical for facility managers and public safety officials.

16.5 Challenges

To date, there have been limited efforts towards researching the role of cyber-physical social systems in facility management. To further this vision, there is a need to address the following questions: (1) how can useful information be discovered from heterogeneous social sensor networks? (2) How can information that is useful to facility managers and building users be detected? and (3) How can this information be successfully communicated? These questions can be addressed via some of the following major research areas:

- Interdisciplinary research: Cyber-physical systems-based facilities management can be viewed as a socio-technical ecosystem of technology, people and information. From systems and control theory point of view, this is a complex and dynamic system with issues that can be successfully addressed through a multidisciplinary approach. As such, the design and sustenance of such a system needs to bring together construction engineers, computer scientists, economists, and social scientists.
- Data-driven control: Due to the availability of large amounts of data in the social environment, there are opportunities to develop new algorithms for optimization and control that are driven by (near) real-time data. In addition, the heterogeneous nature of the data motivates the need for software platforms that break the current technological and organizational silos.

- Sensor networks: Strategies for capturing and harvesting cooperative social data is the starting point for a cyber-physical social systems-based facility management. The main challenge is the heterogeneous and dispersed nature of the data sources required. Another challenge is the design of sensing technologies to interact with the data sources. Such sensing systems need to be designed to source and collect data.
- Security and privacy: The collection and processing of human data is subject to cultural, legal and economic regulations.

16.6 Conclusions

The management of facilities can significantly benefit from the proliferation of innovative technologies. Greater benefits can be derived from these technologies if the social aspect and interaction between humans and facilities are considered. As human-centric computing continues to rise, there is a need to drive the focus from the fully automated cyber-physical systems approach to cyber-physical social systems that capture the social characteristics and interaction of building users and stakeholders. The impact of the solutions offered by cyber-physical social systems are far-reaching; particularly, in reducing energy cost of facilities, improving building occupant's comfort, efficiency and productivity, and enhancing the design of maintainable facilities. Cyber-physical social systems also promise to assist with the identification of more significant issues such as broken faucets, leaking ceilings, unclean areas, or other building conditions that would potentially need a quick resolution to minimize any additional risk to the building structure, sustainability, or continued occupancy. However, this vision can be achieved if the multidisciplinary nature of cyber-physical systems approach is leveraged in the development of methods, science, and models, for extracting, aggregating and mining social interaction data.

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Chapter 17
Urban Building Energy CPS (UBE-CPS): Real-Time Demand Response Using Digital Twin

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17.1 Introduction

Cities are facing unprecedented growth with an increase in population and urbanization. The United Nations estimates that the global population will increase to 9.3 billion by 2050, which is an increase of 30% compared to the population in 2011. As development in dense urban areas continues, the scientific community must continue to observe, analyze, and interpret the effects of dense urbanization, including climate change impacts on urban sustainability, particularly buildings. According to Fathi and Srinivasan (2019), global environmental challenges have led city governments to gradually modify their decision policies towards green and energy efficient approaches. Governments have set ambitious goals in reducing their Greenhouse Gas (GHG) emissions, such as 80% by 2050 in New York [1] and Boston [2]. According to United Nations World Population Prospects, by 2050, two-thirds of the world's population will be urban, rising the negative effects of climate change and the importance of seeking practical solutions. Among all sectors, buildings account for a major part of energy use worldwide and over 60% of this is used for Heating, Ventilation, and Air-Conditioning (HVAC) purposes alone. Energy use is an essential factor in Building Energy Management Systems (BEMS) and Planning Support Systems (PSS) in sustainable urban development (Mohammadi et al. 2013). Therefore, it is essential to develop and implement efficient methods to optimize the energy use of buildings, thereby, reducing their environmental impacts related to operational energy use not just for a single building, but for the town and gown communities.

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The city governments are gradually modifying their policies, decisions, and strategies towards green and energy efficient approaches. Particularly, decisions related to expanding energy generation facilities are critical. To give an example, the local Gainesville Regional Utility (GRU), a City of Gainesville- owned utility estimated the future energy demand erroneously by a significant margin, >30%. Such erroneous future demands may lead to over-sizing the generation facilities which may divert revenues from other priorities, thereby, wasting priced resources. Additionally, cities need to manage its energy, now and in future, as it moves toward time variable sources of renewable energy such as solar and wind. The continuous construction, expansion, and grounds improvement of gown communities may affect the already strained energy grid supplying the town communities. Among others, a robust, bottom-up, physics-based Urban Energy Models approach can virtually test the feasibility of implementing green building technologies on a city-wide scale for energy policy decision-making. UEM can help as effective tools in numerical simulation and optimization of building energy loads for the cities and in result, support the City Managers in their decision-making towards sustainable urban development (Davilla et al. 2016). The challenge is to test the feasibility of implementing green building technologies on a city-wide scale for energy policy decision-making.

Recently, there has been an explosion of urban scale modeling efforts; four major approaches have been attempted: the first of these approaches uses simple building stock for scaling energy assessment from individual buildings to urban-level without considering the influence of building location and their urban contexts (Booth et al. 2012); the second considers urban context in modeling, but is difficult to implement (Pisello et al. 2012; Wong et al. 2011); the third uses energy simulation methods for urban environment such as CitySim and UMI; however, as stand-alone software, they require vast data alteration and reconstruction from ArcGIS data (Reinhart et al. 2013; Robinson et al. 2009) and preliminary work in modeling-simulation-visualization platforms (Srinivasan et al. 2012, 2013, 2014); and the fourth is specific to the Light and Thermal (LT) model based on raster GIS data, and the function is limited due to specific assumptions of occupant behavior (Ratti and Richens 2004).

Yet, they lack the science of identifying and applying low and high impact scenarios directly to building energy simulations, and to provide design adaptation strategies which can lead to policy decision-making by the university and city communities. The challenge is to test the feasibility of implementing green building technologies on a city-wide scale for energy policy decision-making. Although, several researchers have attempted to forecast urban-scale building energy consumption using statistical modeling approaches such as statistical regression, conditional demand analysis, and machine learning, only a few attempted to study the impact owing to climate change. Readers are directed to a systematic review of machine learning applications in urban building energy performance forecasting by Fathi et al. (2019). Most recently, Im et al. (2019a) used statistical regression models to forecast university-wide building energy use for the year 2054 with building characteristics (area; lighting and equipment power densities; U-factor of roof, wall, and windows; building age; years after last building renovation, and window-wall ratios) and weather data such as temperature and humidity. Although the results were promising, these models need significant improvement for better accuracy. For example, the inclusion of high-resolution indoor ambient temperature, lighting levels, occupant interaction with building components, etc. as additional independent variables may enhance the model prediction. However, such data is currently unavailable and poses a threat to predict urban building energy use with higher accuracy.

In this chapter, we discuss the development of a novel Urban Building Energy CPS (UBE-CPS) framework that bridges the physical and the digital world through seamless data transfer for real-time demand response. While the data from physical world relates to sensor data obtained from buildings, the digital world is the Digital Twin, an advanced machine-learning model that is coupled with urban-scale EnergyPlus™ models that represent individual buildings.

17.2 Urban Building Energy CPS

UBE CPS comprises of two layers namely the UEM development, training, and validation layer and the decision system for loads layers, see Fig. 17.1. While the first layer relates to the physical world that includes (1) the actual data (electricity use, ambient temperature, lighting level, occupant interaction with building

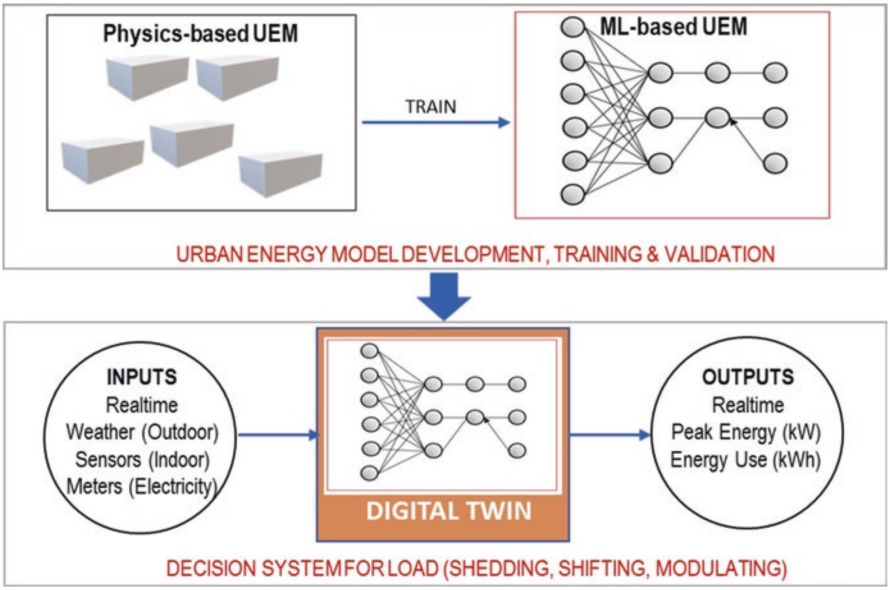


Fig. 17.1 UBE CPS framework

components) from individual buildings and (2) the modeling of these individual buildings in EnergyPlus™ building energy simulation algorithm (EnergyPlus™ models represent individual buildings' spatial configuration, material composition such as thermo-physical properties, and occupancy). In this physical layer, while electricity use can be tracked from utility-installed smart meters, indoor environmental and occupant data can be sourced via a custom-built smartphone app. The second layer includes the digital world which comprises of a Digital Twin, an advanced machine learning model that is coupled with urban-scale EnergyPlus™ models. The high-resolution weather and sensor data (from utility smart meter and smartphone app) are fed to the Digital Twin to predict peak energy consumption, understand the load pattern, and optimally respond to electricity demand.

Our novel UBE CPS framework will help in effective decision-making and policy revisions for built environment regulations such as (a) estimating future energy demand due to population growth, climate change, etc.; (b) implementation of local regulations such as LED light, double pane windows etc., and its effect on the grid; (c) finding optimal standards of construction of future building such as heat transfer coefficient of walls, roof, etc.; (d) helping in understanding of how to balance the energy mix in the future as the city integrates different renewable energy technologies which are extremely seasonal; and (e) achieving an innovative strategy for investing in green and energy efficient technologies and assess the best Return of Investments (ROIs) of green technologies. At this time of writing this chapter, the physics-based UEM and the ML based UEM were under development independently of each other. The following sections discuss the physics-based UEM in detail.

17.3 Urban Energy Modeling: City of Gainesville

Our Urban Energy Modeling (UEM) methodology to study the impact on the City of Gainesville residential building owing to climate change follows a four-step process – (1) Module 1 – Residential building input data creation, (2) Module 2 – Automated EnergyPlus™ input data file creation, (3) Module 3 – Energy simulation in distributed computing network, and (4) Module 4 – Model calibration and forecasting energy use owing to climate change. Each of the modules is discussed in detail in the following sub-sections. The City of Gainesville, FL, comprises of over 40,000 residential buildings. Data related to construction type, building system efficiencies, etc., were obtained from open-source county appraiser website. Extensive data cleaning and preparation was completed using ArcGIS. The data for the building footprint were obtained as GIS files for each property in the city. Several algorithms were developed to extract data to seamlessly create EneryPlus™ input files (.IDF) using python script. Data related to thermo-physical properties were automatically populated in the IDF files based on when the building was built complying with Florida Building Code - Residential. To reduce the overall time for simulation, we custom-built software tool to execute all 40,000+ EnergyPlus models. Essentially, we ran multiple instances of EnergyPlus on multiple cores to reduce the overall time for simulation. The calibrated results were incorporated into DSIM workbench, which allows seamless analysis across the neighborhood and building levels.

17.3.1 Module 1 – Residential Building Input Data Creation

In this module, we compile all the publicly available residential building data for use in the creation of EnergyPlus™ input definition files, see Fig. 17.2. Essentially, after data cleaning, we parse the data from several sources and create individual text files (.txt extension) representing individual residential buildings in the City of Gainesville. Among others, two important sources of data are the Alachua County Tax Appraiser and Gainesville Regional Utility (GRU), the local utility company that serves the City of Gainesville residents.

The first step is obtaining the building data from the Appraiser website. The Property Code Number is also retrieved from the website. The following data is collected and combined: property type, floor height, roof construction material, floor construction materials; style of roof; building type (commercial, single family, multifamily), window type (single glazed, double glazed), wall type, type of air-conditioner, number of bedrooms and bathrooms (see other data collection approaches by Issa and McLaughlin (2019) and Ock et al. (2016). The inferred variables are based on other parameters such as envelope leaks (based on age of building), duct leaks (based on age of building), coefficient of performance of the air-conditioning systems, and approximate plug loads. Besides, retrieving the

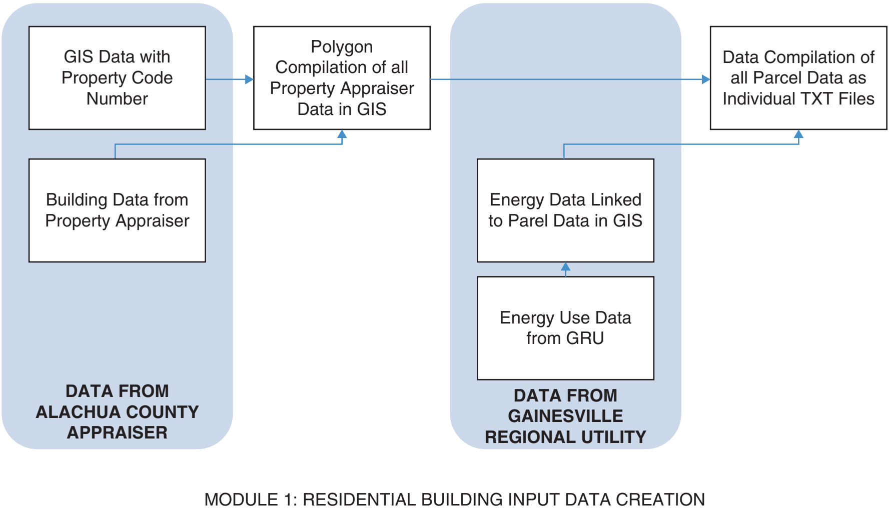


Fig. 17.2 Module 1 dataflow diagram

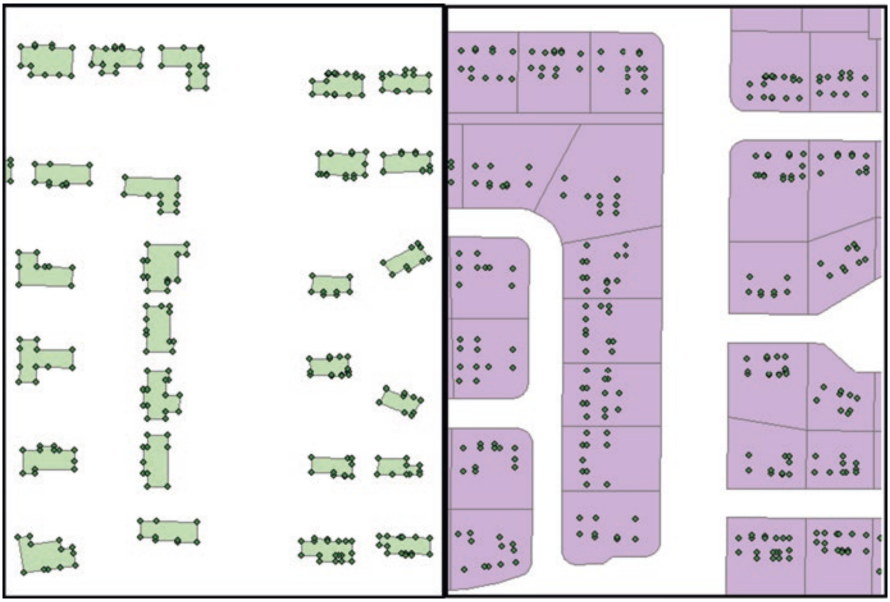


Fig. 17.3 GIS data showing the building footprints

building characteristics from the Appraiser website, we also compile the building footprint data. Figure 17.3 shows the building footprints in GIS.

The second step is the use of energy use data from GRU; these are linked to the Parcel Data, in this case, essentially, the Property. We developed algorithms convert polar coordinates into localized cartesian coordinate system. The 2D information which also contains orientation is later combined with the height and roofing information to yield 3D matrix data of each property. The data is used to create EneryPlus™ input definition files using python script as discussed in Module 2.

17.3.2 *Module 2 – Automated EnergyPlus™ Input Data File Creation*

In this module, we automate the creation of EnergyPlus™ input definition files for modeling purposes, see Fig. 17.4. Each IDF represent an individual residential building in the City of Gainesville, see Figs. 17.5 and 17.6. For the purposes of this project, we utilize state-of-the-art energy simulation engine, EnergyPlus™, which is an approved software by the U.S. Department of Energy. All the variables mentioned in the report have to be entered using a particular syntax in the .IDF file. The advantage being that IDF is a text file and we can easily write scripts to edit it. For this purpose, we created several python functions to allow us to compile data from module 1 to create IDFs, see Table 17.1. The materials for buildings

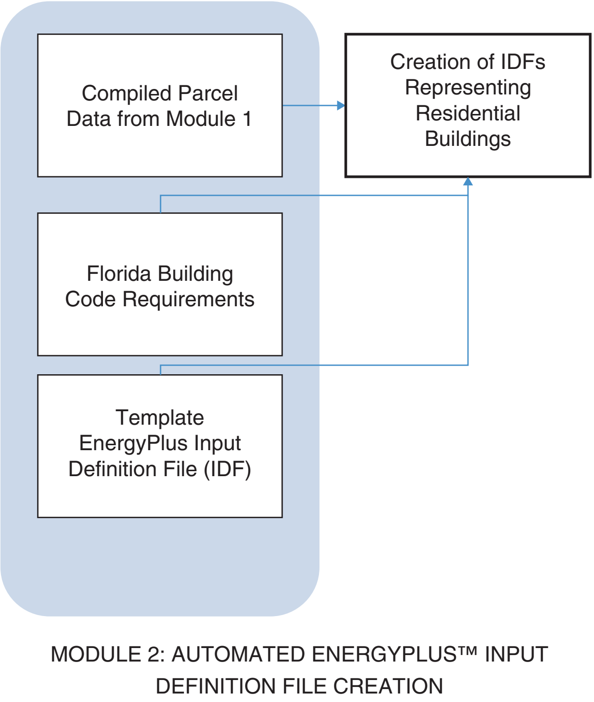
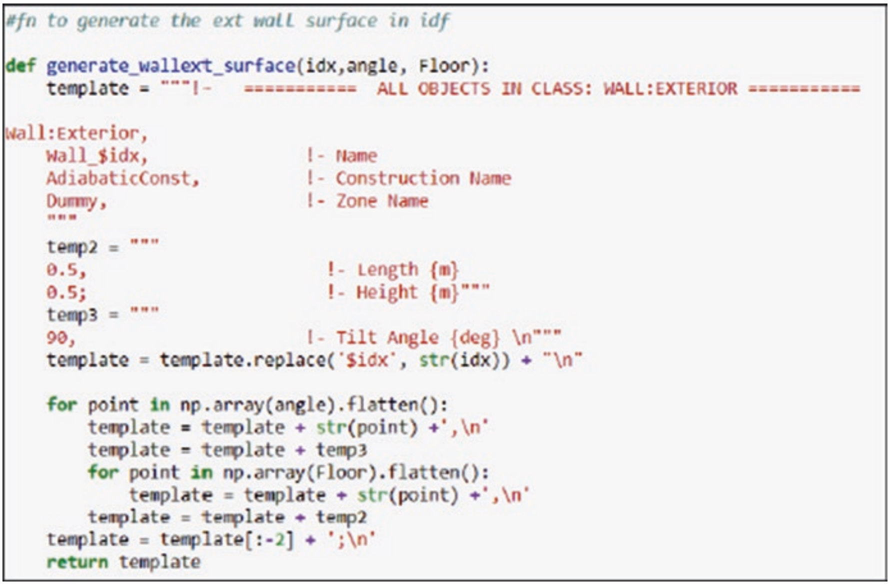


Fig. 17.4 Module 2 dataflow diagram



```
#fn to generate the ext wall surface in idf

def generate_wallext_surface(idx,angle, Floor):
    template = """!-   ===========  ALL OBJECTS IN CLASS: WALL:EXTERIOR ===========

Wall:Exterior,
    Wall_$idx,                !- Name
    AdiabaticConst,           !- Construction Name
    Dummy,                    !- Zone Name
    """
    temp2 = """
    0.5,                        !- Length {m}
    0.5;                        !- Height {m}"""
    temp3 = """
    90,                       !- Tilt Angle {deg} \n"""
    template = template.replace('$idx', str(idx)) + "\n"

    for point in np.array(angle).flatten():
        template = template + str(point) +',\n'
        template = template + temp3
        for point in np.array(Floor).flatten():
            template = template + str(point) +',\n'
        template = template + temp2
    template = template[:-2] + ';\n'
    return template
```

Fig. 17.5 Example code snippet: Generating external wall surfaces from the building footprint

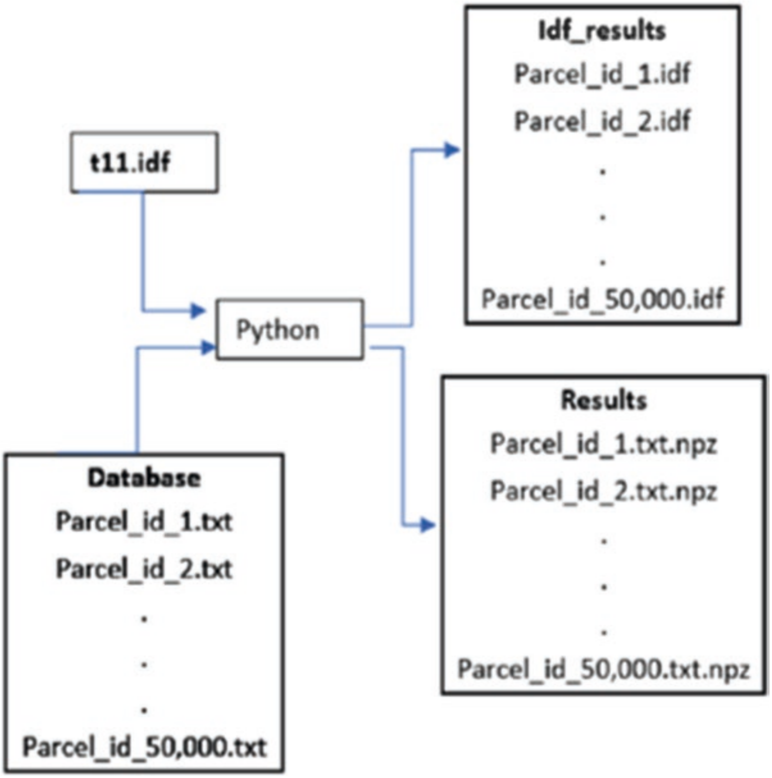


Fig. 17.6 File types used to create EnergyPlus™ input definition files

were selected based on the built year or the year of refurnishing. All the building materials comply with the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) building code, see Table 17.2. The correlation between the thermal conductivity (k) and optimum thickness (xopt) of insulation material is non-linear which obeys a polynomial function of xopt = a + bk + ck2, where a = 0.0818, b = −2.973, and c = 64.6 (Mahlia et al. 2007). The geographical coordinates of each building were extracted. All the values were converted from degrees to meters and a local coordinate system was established for each individual building where the first coordinate of the building was taken as the reference point (the origin). All the buildings were assumed to be at an angle of 90 degrees from the ground and the azimuth angles were calculated for each wall of each building.

Table 17.1 List of python functions created for the purpose of creating EnergyPlus™ IDFs

S.No.	Function name	Description
1	*calculate_initial_compass_bearing*	azimuth angle
2	*thickness_wall*	thickness wall
3	*conductivity_wall*	conductivity wall
4	*R_value_wall*	R value of wall
5	*density_wall*	Density of wall
6	*Sp_heat_wall*	Specific heat of wall
7	*thickness_roof*	Thickness of roof
8	*conductivity_roof*	Conductivity of roof
9	*R_value_roof*	R value of roof
10	*density_roof*	Density of roof
11	*sp_heat_roof*	Specific heat of roof
12	*cop*	COP of HVAC
13	*area*	To find if area is + or -ve (To find mirror images of polygon)
14	*limit_precision*	to restrict measurement to 0.1 mm
15	*generate_wall_surface*	to input wall coordinates in correct order
16	*generate_roof_surface*	to input roof coordinates in correct order
17	*generate_floor_surface*	to input floor coordinates in correct order
18	*generate_wallext_surface*	to input azimuth angle and floor coordinates
19	*generate_wall_ad_surface*	wall coordinates
20	*generate_roof_ad*	roof coordinates
21	*generate_floor_ad*	floor coordinates
22	*generate_windows_surface*	window coordinate
23	*generate_living_fur*	Volume of furniture
24	*generate_partition*	partition area
25	*generate_wall_conv*	changes the name of the wall (e.g., wall01, wall02 etc.)

17.3.3 Module 3 – Energy Simulation in Distributed Computing Network

In this module, we use distributed computing network to perform simulations of over 40,000 EnergyPlus™ models, see Fig. 17.7. The EnergyPlus™ file for a typical building takes approximately a minute to run on a dual core computer. EnergyPlus™ is a multithread application not optimized for parallel runs. However, for our test case the result of one file are completely independent of another, hence we will be running multiple instances of EnergyPlus™ on a supercomputer using multiple cores. We will be running the models using GRAPLE which is a R-based open-source software product of GRAPLE, the GLEON Research and PRAGMA Lake Expedition. GRAPLEr has been successfully used for similar use cases for lake modeling.

Table 17.2 Characteristics of florida energy code (adapted from Kim 2018)

Energy code year	1979	1980	1982	1984	1986	1989	1991	1991R	1993	1997	2001	2004	2004R	2007	2010	2014
Begin date	80.1.1	80.5.1	82.9.1	84.4.1	86.1.1	89.1.1	91.1.1	92.1.1	93.1.1	97.11.1	02.3.1	05.10.1	06.12.8	07.1.1	10.1.1	14.1.1
House type *Wood frame; 3 bedroom; square; slab-on-grade*																
Floor area	1736	1749	1767	1784	1851	1929	1976	2007	2053	2141	2225	2273	2308	2308		
Slab edge	R = 3.4	R = 3.4	R = 0	R = 0	R = 3.5	R = 3.5	R = 3.5	R = 3.5	R = 3.5	R = 3.5	R = 3.5	R = 3.5	R = 3.5	R = 0	R = 0	R = 0
Walls	R = 0	R = 0	R = 11	R = 11	R = 19	R = 19	R = 19	R = 19	R = 19	R = 19	R = 11	R = 11	R = 11	R = 13	R = 13	R = 13
Ceilings	R = 17.2	R = 17.2	R = 19	R = 19	R = 30	R = 30	R = 30	R = 30	R = 30	R = 30	R = 30	R = 30	R = 30	R = 30	R = 30	R = 30
Roof/attic *Composition shingle on felt on plywood on trusses with vented attic*																
	R = 2	R = 2	R = 2	R = 2	R = 5	R = 5	R = 5	R = 5	R = 5	R = 5	R = 5	R = 5	R = 5	U = 0.75	U = 0.75	U = 0.75
Windows																
% WFA	15%	15%	15%	15%	15%	15%	15%	15%	15%	18%	18%	18%	18%	18%	20%	20%
Area(sq.ft.)	260	262	265	268	278	289	296	301	308	385	400	409	415	415		
U-factor:	1.3	1.3	1.3	0.87	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.75	0.75	0.75	0.75
SHGC:	0.75	0.75	0.75	0.75	0.66	0.66	0.66	0.66	0.66	0.66	0.4	0.4	0.4	0.4	0.3	0.3
Envelop																
Leakage (ach50)	12.4	11.8	10.8	9.9	9	7.9	7.3	7.1	6.8	6.1	5.7	5.6	5.6	5.6	5.6	5.6
Heating	Strip	Strip	Strip	Strip	Strip	Strip	Strip	Strip	Strip	Strip	HP	HP	HP	HP	HP	HP
HSPF:	COP = 1	COP = 1	COP = 1	COP = 1	COP = 1	COP = 1	COP = 1	COP = 1	COP = 1	COP = 1	6.8	6.8	7.7	7.7	7.7	7.7
Cooling	6.1	6.8	8	7.8	9	9	8.9	10	10	10	10	10	13	13	13	13
HW system EF																
EF	0.81	0.81	0.81	0.83	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.92	0.92	0.92	0.92	0.92
Tank (gal)	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40
Ducts																
Leaks (Qn)	0.12	0.12	0.12	0.12	0.12	0.12	0.1	0.1	0.08	0.08	0.08	0.06	0.06	0.05	0.05	0.05
R-value	4.2	4.2	4.2	4.2	4.2	4.2	6	6	6	6	6	6	6	6	6	6

Energy code year	1979	1980	1982	1984	1986	1989	1991	1991R	1993	1997	2001	2004	2004R	2007	2010	2014	
Location	Attic	Attic	Int.	Int.	Attic	Attic	Attic	Attic	Attic	Attic	Attic	Attic	Attic	Attic	Attic	Attic	
AHU	Garage	Garage	Garage	Garage	Garage	Garage	Garage	Garage	Garage	Garage	Garage	Garage	Garage	Garage	Garage	Garage	
Other (kWh/year)																	
Miscellaneous	2159	2185	2219	2252	2382	2534	2625	2685	2774	2945	3108	3201	3269	3269			
Lighting		1844	1854	1868	1882	1936	1998	2036	2061	2097	2168	2235	2273	2301	2301		
Refrigerator		1335	1335	1335	1211	1211	1033	969	969	749	749	607	610	610	613		
Dryer		891	891	891	891	891	891	891	891	891	891	891	891	891	891	891	891
Range		447	447	447	447	447	447	447	447	447	447	447	447	447	447	447	447
Dishwasher		145	145	145	145	145	145	145	145	145	145	145	145	145	145	145	145
Washer		105	105	105	105	105	105	105	105	105	105	105	105	105	105	105	105
Pool pump		0	0	0	0	0	0	0	0	0	0	0	0	0	0		
Ceiling fans		382	382	382	382	382	382	382	382	382	382	382	382	382	382	382	382

1979: Section 502.2, “Model Energy Efficiency Building Code.” Florida Department of Administration, State Energy Office, November, 1978
1980: Section 502.2, “Model Energy Efficiency Code for Building Construction.” Florida Department of Community Affairs, Bureau of Codes and Standards, October 1, 1980
1982: Section 903.11, “Model Energy Efficiency Code for Building Construction.” Florida Department of Community Affairs, Codes and Standards Section, September, 1982
1984: Section 1002.1, “Energy Efficiency Code for Building Construction.” Florida Department of Community Affairs Energy Code Program, April 1984
1986: Form 900-A-84, “Energy Efficiency Code for Building Construction 1986.” Florida Department of Community Affairs Energy Code Program, Revised January 1987
1989: Form 900-A-89, “Energy Efficiency Code for Building Construction 1989.” Florida Department of Community Affairs Energy Code Program, 1989
1991: Form 900-A-91, “Energy Efficiency Code for Building Construction 1991.” Florida Department of Community Affairs Energy Code Program, 1991
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1997: Form 600A-97, “Energy Efficiency Code for Building Construction, 1997 Edition.” Florida Department of Community Affairs, Building Codes and Standards Office, 1997
2001: Form 600A-01, “Florida Building Code 2001, Chap. 13, Florida Energy Efficiency for Building Construction”
2004: Form 600A-04, “Florida Building Code 2004, Chap. 13, Florida Energy Efficiency for Building Construction”
2007: Section 13–613, Proposed Modification No. 2367, “Florida Building Code 2007, Chap. 13, Florida Energy Efficiency for Building Construction”
2010: “2010 Florida Building Code: Energy first printing, Chap. 4, Residential Energy Efficiency”
2014: “Florida Building Code fifth Edition (2014) Energy Conservation, Chap. 4, Residential Energy Efficiency

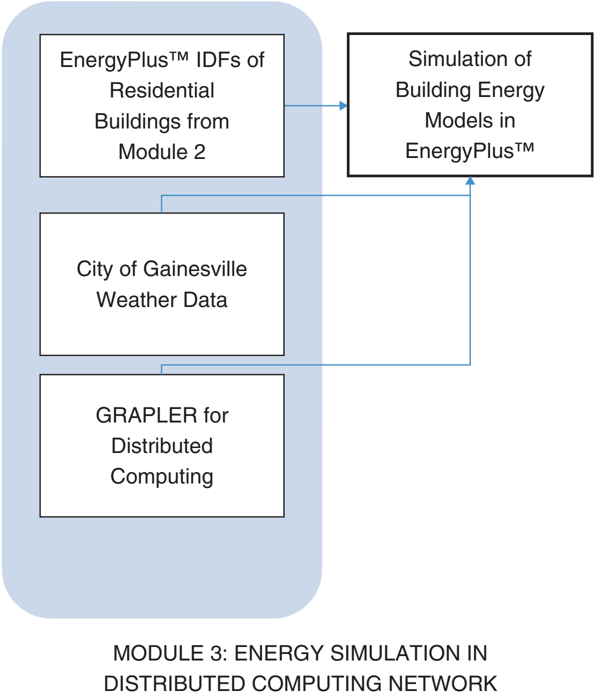

Fig. 17.7 Module 3 dataflow diagram

17.3.4 Module 4 – Model Calibration and Forecasting Energy Use Owing to Climate Change

In this module, the results obtained from module 3 is calibrated with actual energy use data from GRU. The calibrated model is, then, used as the baseline model for use in assessing the future climate change scenarios, Fig. 17.8. Future climate scenarios (weather files related to the City of Gainesville) were created by a proprietary algorithm developed by SeventhWave, a not-for-profit company in Madison, Wisconsin. Their algorithm uses climate change variables from NARCCAP, an international program that serves high resolution climate scenario needs of the United States, Canada, and northern Mexico, using regional climate model, coupled global climate model, and time-slice experiments. Although the dataset is available for public access through the NARCCAP website, they support only raw data on current and future climate variables. The future climate scenarios supported by the NARCCAP have 8 different time series: 2038, 2041, 2046, 2051, 2057, 2063, and 2066. After a thorough study of the future weather datasets, for the purpose of this

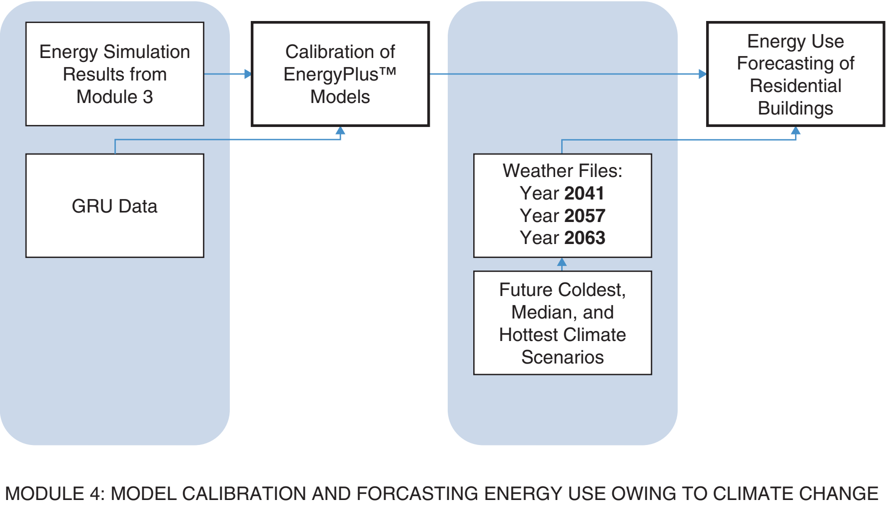

Fig. 17.8 Module 4 dataflow diagram

project, the following three future years were considered owing to their impact to the City of Gainesville; Coldest Scenario: Year 2063; Median Scenario: Year 2041; and Hottest Scenario: Year 2057.

17.4 Conclusions

This chapter discussed the development of a novel Urban Building Energy CPS framework that bridges the physical and the digital world through seamless data transfer for real-time demand response and to accurately predict the demand of these communities in the future and mitigate risks. Through a feedback loop to the City Utility Manager / Administrator, UBE-CPS will become an integral part of the city energy management to automate and, potentially, control building-level demand curve to satisfy grid-level demand response. Although the physics-based Urban Energy Modeling of the City of Gainesville, Florida is discussed in this chapter, work is in progress in the development of machine learning based Urban Energy Model. Some preliminary work using a university campus setting has been already tested; refer Fathi and Srinivasan (2019) and Im et al. (2019a, b).

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Chapter 18
CPS-Based Transactive Energy Technology for Smart Grids

Mohammadreza Daneshvar and Somayeh Asadi

18.1 Introduction

In recent years, various technologies have appeared with considerable developments in different fields of science. This progress has been made to properly respond to the changes in our living environment. For example, in the power system, the emergence of smart devices in buildings and other levels of the system have increased people's desire to have lifestyle conveniences through appropriate usage of intelligent devices. All of these developments have been planned with the aim of improving the quality of life and filling the present gaps in the living environment. In this regard, electrical energy is taken into account as a fundamental form of energy that can easily be converted to other forms of energy for social and economic objectives (Yu and Xue 2016). The electrical network is developed as the infrastructure backbone for reliable energy delivery to consumers and is essentially integrated with controllable devices and physical networks for achieving this vital goal (Yu et al. 2011). Given the significant advantages of electricity in comparison with other carriers of energy, the popularity of this type of energy is increasing day by day, leading to massive growth in the penetration of electricity-based systems in the living environment. This issue has led to a significant increase in energy consumption in the power grid and has provided the power system with the challenge of continuous, economic, and clean energy supply (Daneshvar et al. 2019e). Given this challenge, environmental problems and limited availability of the non-renewable energy resources have made the operation of new units of conventional power plants an inappropriate choice to overcome the crisis of increasing energy consumption. This

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is because renewable energy resources (RERs) are considered carbon-free and cost-effective energy production units that are widely intended in the future built environment policies (Daneshvar et al. 2019b). However, the unpredictability feature of the RERs has made their high level of operation in the power grid a challenge (Daneshvar et al. 2019d). Indeed, RERs are generally harder to harvest, which means appropriate technologies are necessary to ensure their efficient operation.

In the light of the above, it is necessary to have a revolutionary rethinking of the operation of energy systems in accordance with the smart built environment policies, which includes the operation of the power system in a more effective, efficient, environmentally sustainable, and economical way. In this respect, modern grids are introduced as a new paradigm for energy generation, supply and consumption to suitably respond to the aforementioned challenges in building a smart living environment. They are targeted to intelligently integrate smart devices with physical systems by developing control centers powered by advanced algorithms and protocols to efficiently deliver secure, reliable, and sustainable energy to the load centers while ensuring economic and environmental issues. Indeed, the seamless integration of the multi-carrier energy network infrastructure as the physical systems, and bi-directional communication protocols, information monitoring, control, and intelligence as the cyber systems is a key step for the successful implementation of the modern multi-carrier energy networks. Therefore, the need for the integration of the physical systems as well as establishing affordable interactions and wide interoperability between controllable systems with control centers through cyber systems have recently led to the development of a new type of technology platform termed cyber-physical systems (CPSs).

Due to the advantages of CPSs, it is expected that adopting this technology in smart grids will make them more economically viable, more responsive to various users, more efficient in operations, and environmentally sustainable. These remarkable features of the CPSs have led to an increase in attention to their applications in recent studies. Therefore, several effective studies have been conducted regarding the important role of CPSs in different fields. For example, the CPSs framework is used for the smart built environment in Srewil and Scherer (2019) with the aim of analyzing the challenges ahead of modeling the CPSs considering the efficient operation of the communication, control, and computational systems. The potential of the CPSs in the built environment from the different aspects is investigated in Shelden (2018) to clearly identify that the capabilities of the CPSs are limited neither to synergies between physical production systems and their digital forms nor between actual and simulated operational performances. The authors in Mangharam et al. (2016) examined the five challenge problems regarding the foundations of CPSs. This study focused on the challenges of the tight coupling between communication, control, and computation in CPSs. Moreover, in Zhang et al. (2018), the authors have proposed a CPSs-based approach with the aim of guiding occupants regarding the emergency evacuation signage in intelligent buildings.

Although CPSs are taken into account as the necessary tools for the smart built environment, they cannot support almost all challenges in the multi-carrier grid modernization process. Future energy networks aim to involve numerous RERs with a large amount of uncertainties. In such conditions, multi-carrier energy networks need sustainable technologies to establish a dynamic energy balance for reliably continuous energy supply. Therefore, transactive energy is proposed as the network-based technology for dynamic energy balancing, which will play a vital role in building future smart energy environments. The capability of this technology in creating effective interoperability between intelligent elements has led to growing interest in it in recent studies. For example, the impact of the attacks on the load and price signals is scrutinized in Jhala et al. (2019) considering the transactive energy framework incorporated with the physical grid. In Liu et al. (2018), a novel transactive energy control mechanism is proposed to enable energy trading between networked microgrids to enhance the effective usage of the stochastic producers' output. The authors in Nizami et al. (2019) have presented a transactive energy management framework to optimize the energy cost of residential buildings as well as appropriately address grid overload. In this study, a multi-agent system architecture is employed for the realization of decentralized coordination. Additionally, a complete simulation-based transactive energy valuation approach is developed in Huang et al. (2018) to identify the valuable application of the transactive energy technology in the integration of the distributed energy resources (DERs) and controllable loads considering the grid modernization protocols.

Given the key roles of CPSs and transactive energy technology in the smart built environment process, this chapter is concerned with their integrative role in smart grids.

18.2 Transactive Energy: A Novel Energy Technology for a Sustainable Built Environment

Simultaneous increase in energy consumption and emerging the new types of consumers and multi-carrier energy-based systems requires practical solutions to appropriately respond to the energy crisis which seems undeniable in the current era. This issue has made reliable access to efficient, clean, and secure energy as a considerable challenge (Daneshvar et al. 2019a). In this regard, a high operation of the conventional power plants with fossil fuels has been recognized as an unreasonable option for an effective response to the growth in energy consumption due to the significant economic and environmental concerns. Hence, RERs as the cost-effective and environmentally friendly units are targeted to be effectively incorporated with the broader multi-carrier energy networks. However, the unpredictability and intermittency in the RERs outputs have created the fundamental challenges regarding the optimal scheduling of the power grids. This problem has motivated researchers to find practical solutions for effective usage of the clean energy production potential in the network. In this respect, optimal integration of the RERs is proposed as a confident way for the high exploitation of the RERs throughout the electric power system (Daneshvar et al. 2019c). However, network-based technologies are required for reliable optimal integration of the stochastic producers, which can meet the multi-carrier energy networks' requirements from both the economic and environmental overviews. This issue has led to introducing new visions in the smart energy built environment for the future multi-carrier modern energy networks.

Given the aforementioned challenges, the U.S Department of Energy (DOE) has made a GridWise Architecture Council (GWAC) responsible to evaluate strategies for creating suitable interactions between information systems and effective interoperability between automation systems and different technologies (Forfia et al. 2016). This is because the integration of the intelligent elements into the energy internet and information technologies will make the future's multi-carrier energy network infrastructure more efficient, stable, reliable, and secure (Daneshvar et al. 2019f). After the specialized analysis in the GWAC, its representatives introduced a new network-based technology for overcoming the challenges ahead of the renewable-based systems, which is called transactive energy technology. The GWAC defines transactive energy as "a set of economic and control mechanisms that allows the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter (Hammerstrom et al. 2016)." Indeed, the GWAC has attempted to develop energy-environment policies to build a smart environment through promoting the regulated policies for the CPSs and intelligent systems, their investors, and owners. This issue has made transactive energy as a strong contender for coordinated operation of the responsive devices accompanying with high usage of clean energy production capacity in the smart energy built environment (Kok and Widergren 2016). In other words, the GWAC has provided new opportunities for all participants such as CPSs, controllable devices, information and communication systems by proposing transactive energy technology to a widespread presence in the future energy environment for targeted interactions, efficient operations, and successful interoperability. All of these are possible through the appropriate operation of the transactive energy systems (TESs) in the process of the smart energy built environment. Indeed, these operations will be carried out by considering two important factors in the transactive energy architecture i.e. establishing a dynamic energy balance between energy supply and demand and employing economic and control mechanisms for this aim. Given the aforementioned features of the transactive energy, the GWAC has summarized the capabilities and features of this technology, which are listed in Table 18.1 (Melton and Fuller 2016).

Table 18.1 General features of the transactive energy technology

Transactive energy technology is a:
1.novel energy technology to omit all intermediaries for the sustainable energy built environment
2.personal service on energy demand
3.market belongs to the energy suppliers, consumers, investigators, platform providers, and other market participants that create widespread synergies in the marketplace
4.new ecosystem with certain principles and framework that is targeted for creating interactions through the integration of the energy suppliers and buyers with CPSs and information technology

18.3 Transactive Energy Systems in the Smart Built Environment

In recent years, the growth of DERs especially the clean form of them along with the infusion of advanced analytic and information technologies have provided both challenges and opportunities for the continued improvement of the current environment. For instance, although DERs can eliminate single points of failures for increasing reliability of the system and improving resiliency, they also expose the energy networks to complex coordination and difficult interoperability that will lead to system implementation and operation with higher cost and lower efficiency (Ambrosio 2016). In this regard, TESs are developed as a promising way to redesign the energy architecture in accordance with the smart built environment protocols. In other words, TESs are recognized as one of the flexible, confident, and scalable ways for developing the present paradigm of the electric power system to the reliable, resilient, and efficient electrification systems considering the grid guidelines in both small and large scales. On another hand, TESs are the collection of the multiple intelligent agents that each of them is scheduled for special responsibility throughout the multi-carrier energy networks. Some of the key responsibilities of the TESs agents in the grid modernization process are demonstrated in Fig. 18.1 (Ambrosio 2016). However, the role of the TESs agents is not limited only to the illustrated examples in Fig. 18.1 and they are also taken into account as the vital players in the smart built environment that enable the implementation of the CPSs in the different scales of the system.

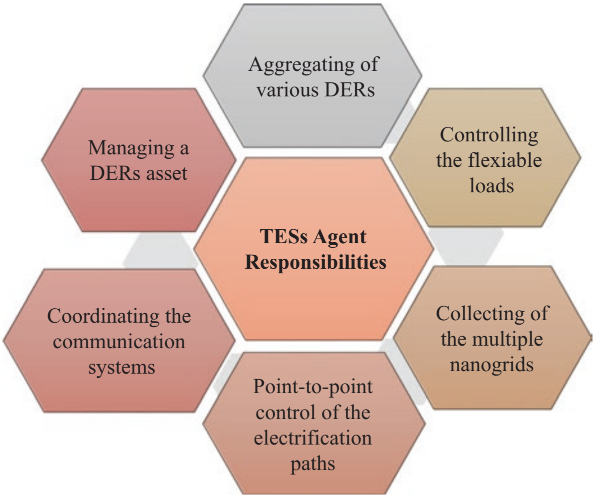


Fig. 18.1 Important responsibilities for the TESs

18.4 Cyber-Physical Security Analysis in Transactive Energy Systems

Due to the TESs ability in addressing the energy management, optimization and interoperability issues, they are intended as the significant tools in building the modern energy environment that will be matured more than ever by assigning value to the different types of the DERs especially RERs and objectives of the system as well as creating variety in providing particular opportunities for the consumers. Effective TESs mechanisms leverage on a communication architecture and the numerous distributed edge-computing (Arman et al. 2018). In this regard, the number of both the internet of things (IoT) devices and distributed edge-computing systems affect the transactive energy paradigms in making autonomous decisions on demand-side energy management. However, both the energy network cyber assets and IoT systems are increasingly vulnerable to destructive attacks. Hence, coordinated operation of the CPSs and TESs is essential for the security of the system in the smart built environment. In this respect, compared with information technology data, cyber-physical TES data are more anticipatable due to continuously performing similar tasks by the CPSs following a physics rule (Garitano et al. 2011). Consequently, because of the widespread information exchanging between various intelligent systems in the transactive energy architecture (Daneshvar et al. 2018a), the related system infrastructure is vulnerable to cyberattacks so that an integration of the CPSs with the TESs is proposed as an effective solution for providing the satisfactory security in the smart built environment.

18.5 The Integrative Role of Cyber-Physical Systems and Transactive Energy Technology in the Built Environment

The significant growth in energy consumption has opened the gateway to the impressive presence of more challenging items such as high usage of RERs in the multi-carrier energy network infrastructure. In this regard, transactive energy technology is proposed as a promising way for optimal integration of the RERs to overcome the challenge of their intermittencies by applying the control and economic mechanisms. This is done in the transactive energy structure by efficient operation of the TESs powered by the intelligent software agents throughout the modern power system. TESs are the collection of smart devices, communication systems, and advanced control centers, which are involved with the high shared renewable-based systems to assist the realization of the grid modernization schemes. In order to meet the mentioned goals in the transactive energy paradigm, the smart built environment process requires redesigning to provide the appropriate conditions for optimal integration of the information technologies, communications systems, energy market-based technologies, and controllable and unpredictable energy production units throughout the multi-carrier energy networks. This integration should be met considering the allowable range of the system reliability, stability, and security that need an overthinking about the efficient construction of the power system infrastructure. Due to this, the capability of the CPSs can be employed accompanying the transactive energy technology to make the realization of the grid modernization plans easier than ever before. This happens because the CPSs are the control-based mechanisms that are monitored using intelligent computer-based software and algorithms under internet protocols (Khan et al. 2017). This feature of the CPSs has been led to the widespread usage of them in critical areas such as autonomous automobile systems and smart grids, which has motivated the researchers to develop them in accordance with the new emerging technologies (Khaitan and McCalley 2014). The integration of the aforementioned technologies not only will make the energy environment more efficient, reliable, secure, and stable than current infrastructure but also provides proper conditions for engaging various capable technologies such as the internet of energy that are necessary for facilitating the implementation of the modern multi-carrier energy networks.

18.6 Cyber-Physical Systems (CPS) in the Smart Grids

In recent years, power grids are developed to respond to some key drawbacks regarding energy generation, control, and management. The centralized power generation process in the current structure of the power system is begun to switch to the smart version of it due to several basic challenges (Järventausta et al. 2010). The remarkable of these challenges are illustrated in Fig. 18.2.

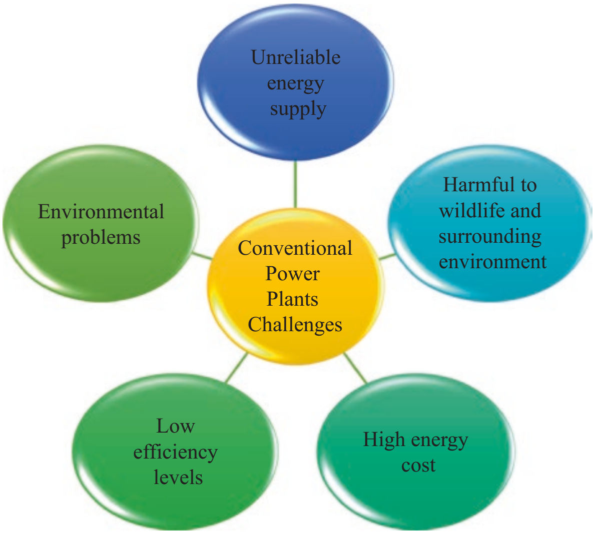


Fig. 18.2 The challenges of conventional power plants

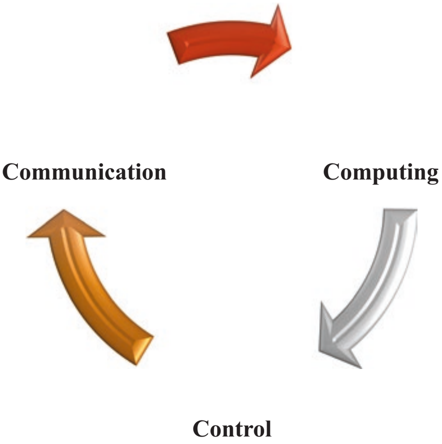
Each of these challenges is briefly described here. As seen in Fig. 18.1, one of the important challenges regarding the centralized power generation is an unreliable energy supply (Bazilian and Onyeji 2012). This is because when one energy production unit with high capacity crashes, the system fails to supply all of the loads in a reliable manner and may even break down. Smart grids with decentralized power production provide a high degree of reliability in supplying energy to the consumers using the various types of DERs throughout the power grid (Bremer and Lehnhoff 2017). In addition, high usage of RERs as a special type of DERs can seriously reduce environmental problems by mitigating greenhouse gas emissions (Tzanakakis et al. 2012). Indeed, smart grids provide an appropriate condition for the operation of numerous RERs by adopting intelligent control mechanisms that make the power supplying process more reliable (Daneshvar et al. 2018b). On the other hand, conventional power units use fossil fuels for generating energy that imposes high energy costs for the energy producers and releases a high amount of greenhouse gas emissions while these problems are solved in the smart grid structure with a high share of RERs (Daneshvar et al. 2018c). To sum up, smart grids have many advantages in comparison with traditional power units with fossil fuels that have attracted a lot of attention in recent years. All of these advantages will be realized by applying sustainable technologies and intelligent control systems to achieve a smart structure of the power grid. In this regard, CPS is one of the important steps of smartization of the power grid that should be developed in accordance with the smart grids' requirements for ensuring the security of the network with numerous smart devices (Yu and Xue 2016).

As mentioned in the previous lines, CPS takes into account as an important part of the smart grid with numerous intelligent devices. CPS system in smart grids consists of three main parts including communication, computing and control which are explained in the following sections:

18.6.1 Communication

As obvious from Fig. 18.3, one of the important parts of the CPS system is the communication links (Karnouskos 2011). Each of the smart devices in the system can analyze their status in terms of energy consumption, efficiency, the amount of releasing greenhouse gas emissions in some cases, etc. These evaluations are made by intelligent algorithms and optimization processes based on the control mechanisms in the CPS system (Cintuglu et al. 2016). The outputs of each evaluation process related to each smart device are sent to the control centers for considering the high level of system assessment. The appropriate algorithms in the control centers process the received data from the controllable devices to adopt the optimal control strategies for making the operational decisions (Sridhar et al. 2011). The final decisions are sent from the control center to the smart devices to operate in the new received set points Fig 18.3.

Fig. 18.3 Three main parts of the CPS system (Xiong et al. 2015)



In this regard, the information can be exchanged between smart devices and control centers in the various communication protocols. One of them is the internet of energy (Bui et al. 2012). Indeed, the internet of energy is taken into account as the special aspect of internet technology that is developed in terms of hardware and software systems to reliably respond to the smart grids' requirements for exchanging information signals between intelligent systems (Daneshvar et al. 2019f). In order to establish widespread and interoperable communication in the smart grids, the internet of energy paradigm has typically employed middleware solutions considering the security issues of the exchanged information (Bedogni et al. 2013).

18.6.2 Computing

Another considerable part of the CPS system is computing devices (Fabbri et al. 2016). Each event in the CPS system should be carefully analyzed using advanced computational systems. Considering the smart grids with a large number of smart devices, the CPS system will need huge computational systems for effectively handling all interactions between the controllable devices throughout the network. This structure will impose a high computational burden on the system and will also increase the complexity of the evaluation process (Tuo et al. 2018). However, these challenges can be solved using smart systems with central computational software. Indeed, the majority of the computational process in the CPS system can be done by smart devices and only their optimal results will be sent to the control center with the aim of comprehensive assessments.

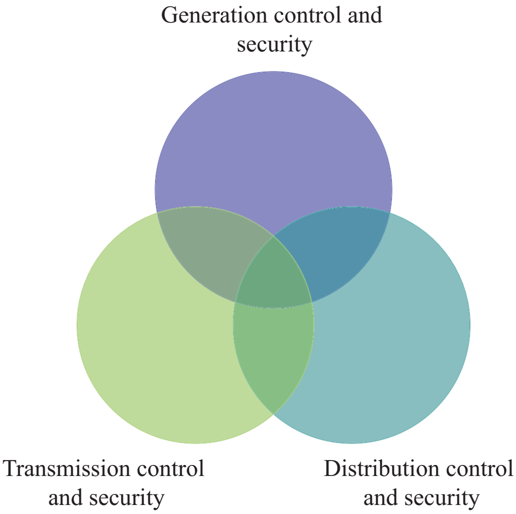


Fig. 18.4 Classification of control loops in the power system

18.6.3 Control

Because the availability of the power grid is more sensitive for continuous energy supplying, all parts of it i.e. generation, transmission, and distribution should be covered by the CPS system for reliable and securely energy supply. In this regard, a typical classification of control loops for the power grids is illustrated in Fig. 18.4 under the CPS protocols (Sridhar et al. 2011).

Control loops in the CPS system are used for identifying the computations, advanced protocols and communication signals, machines and devices, and control actions. In this system, the impacts of cyber-attacks on the control loops are considered to ensure the stability of the power system by adopting appropriate decisions based on the advanced analysis in the system. In this regard, an attacker can exert vulnerabilities and build attack templates with the aim of damaging to the different parts of the system (Huang et al. 2009). Therefore, the careful evaluation of the impacts of these attacks is essential for designing a robust CPS system for the smart grids to guarantee the reliability and security of the power supply (Ma et al. 2018). These impacts can be load shedding or instability of the system that caused by frequency and voltage imbalances in the power grid.

18.6.3.1 Generation Control and Security

Generally, terminal voltage and generator power output are two important factors that are intended to be completely controlled by the control loops in the generation section. The various types of generation control in the power system are demonstrated in Fig. 18.5.

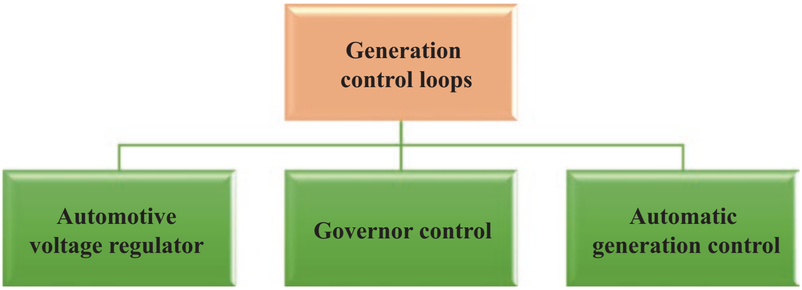


Fig. 18.5 Classification of generation control

Automotive voltage regulator (AVR) is used for keeping the voltage of power generation in the allowable range (Lybbert 2009). The control loop in this regulator checks the amount of voltage in the specific periods and then feedbacks to the control system to make appropriate decisions in keeping the voltage constant by adequate changing the amount of power production. Indeed, AVR is typically employed in the generation section not only to keep the amount of voltage in the acceptable range, but also to reduce the power losses, compensate the voltage drop in the distribution lines, and improve the power quality (Mendoza et al. 2007).

In the control mechanisms of the generation part, the governor is used for balancing frequency in the system (Bogodorova et al. 2015). In the power grid, keeping frequency in the permissible range is necessary for the stability of the system and avoiding any blackout (Bø et al. 2016). Governor is a controller system that can retain frequency in the standard range by controlling the speed of generators. Indeed, the amount of power production can be increased/decreased when the rotor speed of the generator is increased/ decreased by the governor.

Due to the existence of several power generators throughout the power grid, their coordination needs an advanced controller system. For this aim, automatic generator control (AGC) is applied for adjusting the amount of power production by each generator in accordance with fluctuations of the electrical loads. In another word, AGC helps in establishing a balance between energy supply and demand by controlling the electricity generation in the electric power system.

18.6.3.2 Transmission Control and Security

Transmission lines are responsible for transmitting energy in the safe operating margin and the allowable range of voltage (Wermann et al. 2016). To ensure this, transmission control loops are used in the CPS system considering the capacity of the transmission lines as well as their other restrictions. In this regard, some communication protocols are posed to help the transmission system operator to easily control the system. The employed communication protocols in the control loops of the transmission system are demonstrated in Fig. 18.6.

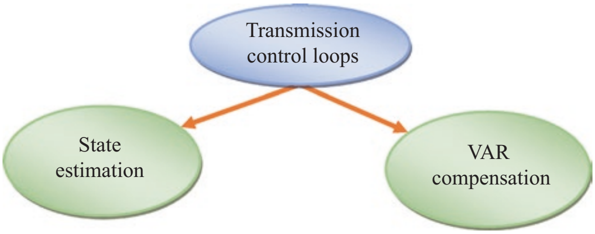


Fig. 18.6 Classification of transmission control

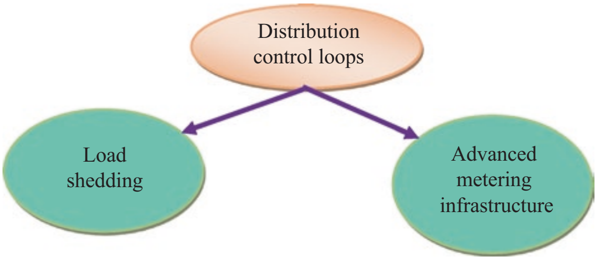


Fig. 18.7 Classification of distribution control

State estimation is a technique for estimating the systems' variables such as phase angle and voltage magnitude (Tripathi et al. 2015). Indeed, state estimation is used in the control process of the transmission system with the aim of giving more details about the amount of voltage and power flows in the various sections of the transmission system to provide an appropriate condition for the system operator to adopt optimal decisions.

In order to improve the system performance, volt-ampere reactive (VAR) compensation is exerted in the transmission system to control the amount of reactive power injection (Fughar et al. 2015). The main objective of this control in the CPS system is to minimize voltage fluctuations in the transmission system, especially at the end of the power lines. In addition, the situations of power transferable and load shedding can also be improved by applying these controlling devices in the transmission systems.

18.6.3.3 Distribution Control and Security

Distribution systems in the smart grids are responsible for delivering continuous energy to the consumers (Dunn et al. 2011). In this regard, many control loops are emerged to directly control the power consumption at the end-user level. Two main control loops in the control process of the distribution system are illustrated in Fig. 18.7.

Load shedding schemes are taken into account as the most famous approaches for demand-side energy management. In the emergency conditions such as a sudden

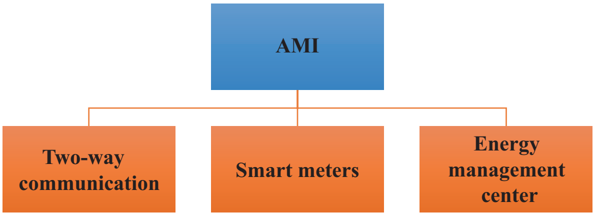


Fig. 18.8 Different parts of the AMI

decline in the production of RERs, one of the effective ways for keeping the stability of the system is curtailing some of the loads in a scheduled manner (Ahsan et al. 2011). This work can balance energy consumption and production with the aim of balancing the voltage and frequency.

Another effective method for controlling the distribution systems is to use of advanced metering infrastructure (AMI). AMI has consisted of three important parts that are shown in Fig. 18.8 (Hansen et al. 2017). In this system, smart meters are used for measuring the amount of real-time energy consumption, voltage magnitude, phase angle, and frequency. All of this information is exchanged between the control center and smart meters through a two-way communication protocol that provides the possibility of receiving optimal decisions from the control center by the smart meters with the aim of controlling energy consumption in the distribution system.

18.7 Conclusions

In this chapter, the integrative role of CPSs and transactive energy technology in the smart built environment was evaluated in detail. This evaluation highlighted that applying the CPSs in the process of the smart built environment is necessary for creating comprehensive coordination between intelligent computational elements and physical systems. On the other hand, for a complete smart built environment, the CPSs need to incorporate the capable network-based technologies to enable smart grids to suitably control, manage and coordinate the intelligent systems. Therefore, this study proposed transactive energy as a sustainable and reliable technology to integrate with the CPSs for smart grids. Indeed, transactive energy technology can provide appropriate conditions for adopting various advanced technologies to the smart grids by employing significant control and economic mechanisms. Thus, a framework with the integration of the CPSs and transactive energy technology not only will make the energy environment more efficient, reliable, secure, and stable than current infrastructure but also provides proper conditions for engaging various capable technologies for facilitating the implementation of modern multi-carrier energy networks.

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Chapter 19
Concluding Notes

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19.1 Introduction

This chapter concludes the book and draws together a number of the threads running through the various chapters. It starts with a brief summary of the contents of the book, restates the main benefits of cyber-physical systems in the built environment, and outlines a number of considerations in the effective development and deployment of CPS in this context. Future directions in CPS application in the built environment are also discussed in the last section of the chapter.

19.2 Summary

The focus of this book has been on introducing the potential of cyber-physical systems in the built environment. This is based on the tremendous potential that it offers for improving various aspects of the built environment and associated processes. The adoption of digital technologies over the last decade have positioned firms involved in shaping the built environment to leverage technologies such as CPS in enhancing both the project delivery process and the quality of the built facilities. There is considerable scope for the use of CPS to add value to the project information communicated in the development and management of the built environment.

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The various chapters of this book have covered different aspects of cyber-physical systems applications in the built environment. Starting with a description of the fundamentals of CPS, the book discusses the technology requirements for CPS and the use of CPS in other industry sectors. It then presents a wide variety of applications, with varying requirements and levels of CPS implementation. Application areas covered include management of heavy construction projects; construction progress monitoring; human-in-the-loop systems for safer construction sites; temporary structures monitoring; intelligent crane operations; smart construction objects; mobile crane safety; CPS model checking; structural infrastructure monitoring; smart transportation systems; component tracking and operation; facilities management; urban building energy systems; smart cities; and smart grids. As can be seen from the above, when effectively and thoughtfully deployed, CPS can deliver benefits that were hitherto unavailable through conventional means. These are discussed in the next section.

19.3 Benefits of Cyber-Physical Systems in the Built Environment

Each of the chapters in this book have either explicitly or implicitly stated the benefits of cyber-physical systems in the built environment. These are briefly summarized here to provide organizations that are involved in the development and/or management of the built environment with a coherent set of potential benefits that can guide their future decision-making:

- Real-time information exchange between the design office and the construction site;
- Reduction of construction risks as activities and processes can be more closely monitored and controlled;
- Accurate as-built models that are useful for the later phases of the constructed facility's lifecycle – commissioning, operation, facilities management, deconstruction, etc.;
- The capacity to actively control key components in the constructed facility beyond the construction stage;
- Improved safety through proactive hazard monitoring; and
- Improved opportunities for more sustainable construction practices;
- Integrated infrastructure management
- Enhanced city operation management through seamlessly connecting various urban infrastructure systems
- Increased capacity for 'What if?' analyses and simulations;
- Numerous additional benefits that derive from real-time process tracking and active component control.

19.4 Lessons Learned from CPS Deployment in the Built Environment

Several important lessons were learned in the development and deployment of cyber-physical systems in the built environment. These include the following:

- It is essential to have a clear understanding of the specific construction problems that the CPS application is intended to tackle. Poor definition of the problem will result in development difficulties and a sub-optimal application;
- The virtual models on which the CPS system is based need to be accurate and up-to-date to ensure effective mapping to the physical entities they represent;
- The bi-directional coordination mechanism is probably the most vital aspect of CPS development and needs to be carefully designed. Otherwise, the binding between computational resources and physical elements will be weak, erratic and inadequate;
- Sensors and sensor networks are very important for live data capture, which is one of the key enablers for CPS. It is important that the most appropriate sensors are selected for use in data collection and transmission between the physical elements and the associated virtual model counterparts. The specifics will depend on the type of application and other hardware and software systems linked to the CPS application;
- Laboratory experimentation is very helpful for establishing the performance of proof-of-concept prototypes prior to real-life deployment on site. Without this, it may be difficult or impossible to distinguish those problems associated with the system design from those that are due to the vagaries of the deployment environment;
- The transition from laboratory to site implementation should not be underestimated as there are numerous practical considerations that need to be taken into account. These include scalability, cost, power supply, wiring, the site environment, people, vehicles, etc. These need to be carefully evaluated and adjustments made to the prototype to maximize the practical benefits.
- Considerable investment of resources is needed for firms in the built environment sector to maintain an appropriate computing and communications infrastructure to support effective CPS deployment. However, the associated benefits are such that the return on investment can be speedily and profitably realized.

19.5 Future Directions for CPS in the Built Environment

While it is impossible to predict, with any accuracy, the future directions for cyber-physical systems in the built environment, it is useful to state that this will be governed by several factors. The two most important of these are technological developments and the emergence of new built environment applications.

19.5.1 Technological Developments

Numerous emerging technologies will affect the deployment of CPS in the built environment. These include context-awareness, unmanned aerial vehicles (UAVs), 3D printing, cloud computing, non-volatile memory, communication networks and 5G, sensor developments, Internet of Things (IoT), blockchain, machine learning and artificial intelligence (AI).

Context-Awareness Context-awareness enables applications to adapt their operations based on the specific context within which they are operating. This enables the delivery of context-specific information and services to end-users and middleware applications. When the sensors on a physical component indicate a change in context, its virtual representation would be automatically alerted and appropriate updates and actions undertaken.

Unmanned Arial Vehicles (UAV) The use of UAVs presents exciting opportunities for CPS use in the built environment as UAVs have the capacity to trigger as well as capture data from both physical elements and virtual models. As such, they can be highly effective in facilitating the bi-directional coordination between physical construction objects and their virtual models. This is particularly useful in situations where access is difficult or inconvenient for humans, and where the capture of digital images is necessary to document changes in the physical environment.

3D Printing 3D printing could be considered as the ultimate cyber-physical system in terms of the fact that it takes a virtual model and then produces the physical component from it. When sensors are embedded in the printed environment, there is the potential to retain the link between the physical component and its digital representation. This opens up the possibility for bi-directional coordination and active control of the component (and possibly, whole facilities) from the digital model.

Cloud Computing Cloud computing enables applications, services and data storage in the ‘cloud’. This enables the rapid and efficient deployment of a wide range of applications without the conventional overhead of fixed services and storage facilities. This can be leveraged to implement CPS applications at a fraction of the cost that would otherwise have been needed. In addition, the real-time connection to cloud servers allows instantaneous data communication and information discovery, as opposed to post-processing of the stored data. This can facilitate the (quasi)real-time applications, which is an essential expectation of the CPS developments.

Non-Volatile Memory As developments in computing memory continue, it is expected that non-volatile memory will become increasingly cheaper enabling sensors and other data capture technologies to hold more data/information for longer without the fear of loss.

Communication Networks and 5G With developments in wireless communication networks, such as the emergence of 5G networks and beyond, it will be increasingly easy to transmit data/information effectively and efficiently between a variety of online applications and between project team members. The connectivity between wireless sensors and other devices with wired systems will also improve making CPS applications more readily deployable.

Sensor Developments Sensors/actuators are becoming increasingly sophisticated in terms of the diversity of sensor types, the range, and type of data/information that they can collect, hold or transmit, and their capacity to work in concert to gather and transmit information. Related to this, is their capacity in proactive control situations to instigate changes in the physical environment and/or virtual models.

Internet of Things (IoT) IoT is increasingly being deployed in a variety of industry sectors, with a few trials being conducted in the built environment sector. The possibility of having large numbers of critical physical elements integrated into an IoT environment would considerably enhance the performance of an appropriately designed CPS system.

Blockchain A blockchain is a time-stamped series of immutable records of data that is managed by a cluster of computers, where each of these blocks of data (i.e. block) is secured and bound to each other using cryptographic principles (i.e. chain). The blockchain network has no central authority and is a shared and immutable ledger, the information in it is open for as users. As such, the applications of CPS in the built environment can particularly take benefit from this emerging technology as it will facilitate the sharing of information among the various transient stakeholders involved in the development/management of the built environment facilities/projects.

Artificial Intelligence (AI) The re-emergence of machine learning and artificial intelligence (AI) and its integration into mainstream applications, often taken for granted by the general public, offers additional possibilities for CPS applications in the built environment. In addition to the bi-directional coordination between physical components and their virtual counterparts, AI-based CPS applications would have the capacity, amongst others, to benefit from machine learning, deep learning, and pattern recognition.

Many of the technologies highlighted above already exist but have yet to be leveraged in the development of CPS applications for the built environment. Additional technologies will emerge that will also have the capacity to influence CPS-based built environment applications.

19.5.2 New Built Environment Applications

New built environment applications for CPS will help shape its future within the sector. Some of those expected in the near future are briefly presented below:

Facilities Management (FM) There is considerable potential for the deployment of CPS in facilities management (FM) as shown by the light fixtures example described earlier. With FM, there is the opportunity for active control of physical elements in the constructed facility from the virtual model.

Smart Cities Another important application area is smart cities, which have been briefly introduced in Chap. 14 within which considerable information and communication technologies, including IoT (Internet of Things), have been deployed. This opens up the possibilities of a more coordinated operation of key facilities/infrastructure in cities, with significant economic and operational benefits.

Infrastructure Management Integrated infrastructure management is a highly appropriate area for CPS deployment. This will entail having a very good understanding of the dependencies between infrastructure systems and how these can be leveraged by CPS for synergistic purposes. There is also scope for improved resilience of these infrastructure systems.

Energy Management A specific aspect of smart city infrastructure that can be enhanced by the CPS application is district-scale energy management. Being able to monitor and track physical energy use at the district scale with a virtual model that can be utilized to optimize energy distribution in real-time based on actual need would be very useful.

Content-Aware Facilities CPS also offers the potential for ‘content-aware constructed facilities’ that have knowledge of what they contain. These contents can be in the form of specific items of equipment (e.g. Automated External Defibrillators, AEDs) or people (e.g. medical or technical personnel). The potential benefits of this in a healthcare facility are considerable, as facility contents can be tracked and directed from the virtual model of the facility.

The above are just a few examples but there are numerous other possibilities.

19.6 Epilogue

It is evident from the various applications described in this book that cyber-physical systems have much to offer the built environment sector. The complexity associated with the delivery of construction projects by a transient project team made up of individuals/teams from a variety of organizations makes the effective deployment of CPS challenging. However, the potential benefits of CPS and associated technologies make it imperative that firms in this sector make the necessary investments to leverage the technologies and reap the attendant benefits.

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