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RESEARCH ARTICLE

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Cyber–physical systems development for construction applications

Abstract Cyber–physical systems (CPS) are intended to facilitate the tight coupling of the cyber and physical worlds. Their potential for enhancing the delivery and management of constructed facilities is now becoming understood. In these systems, it is vital to ensure bi-directional consistency between construction components and their digital replicas. This paper introduces the key features of CPS and describes why they are ideally suited for addressing a number of problems in the delivery of construction projects. It draws on examples of research prototypes developed using surveys, field experiments, and prototyping methodologies, to outline the key features and benefits of CPS for construction applications and the approach to their development. In addition, it outlines the lessons learned from developing various systems for the design, construction and management of constructed facilities, which include building component placement and tracking, temporary structures monitoring, and mobile crane safety. The paper concludes that the construction industry stands to reap numerous benefits from the adoption of CPS. It states that the future direction of CPS in construction will be driven by technological developments and the extent to which CPS is deployed in new application areas.

Keywords cyber–physical systems, components, temporary structures, cranes, sensors

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1 Introduction

The construction industry is traditionally slow in its uptake of new technologies and has been criticized for its lagging productivity relative to other industry sectors (Abdel-Wahab and Vogl, 2011; Bilal et al., 2016). However, the situation is changing and the industry has considerably increased its adoption of information and communication technologies over the last few years. Numerous companies now routinely adopt some level of building information modeling (BIM) or virtual design and construction (VDC). The requirement by some countries (e.g., UK, Singapore, Finland, and Sweden) that firms seeking public sector contracts adopt a certain level of BIM has further propelled industry uptake (Bordel et al., 2017).

The emergence of cyber–physical systems (CPS) offers additional opportunities for the construction industry to leverage technology for improvements to construction processes. This is because those organizations that have adopted BIM/VDC are not reaping the full benefits offered by these systems. For example, there remains a lack of coordination and consistency between the virtual models developed by designers and the physical construction work on the site. Virtual models are developed at the design stage and they are not effectively used (if at all) during the construction stage and beyond.

By providing for tight coupling between computational models and associated physical entities, CPS offer an appropriate mechanism for construction project teams to bridge the gap between virtual models and the physical construction. This will enable a variety of applications, services, and other innovations to be developed and deployed, building on this bi-directional coordination. In particular, it would be much easier to utilize the virtual model as a critical part of the physical construction process.

This paper starts with a brief overview of cyber–physical systems (CPS), including their key characteristics and the bi-directional coordination approach and architecture for achieving CPS. This is then followed by descriptions of

CPS developed for various aspects of the construction process, which include construction component tracking and control, temporary structures monitoring, and safety of mobile cranes. The choice of these application areas is based on the intent to demonstrate CPS applicability across a range of construction applications. A discussion section is presented that focuses on the lessons learned from developing CPS for construction applications, the potential benefits of CPS deployment in construction, the key considerations in the practical deployment of CPS applications in construction, and trends in the future development of CPS applications for construction.

2 Cyber–physical systems

One way CPS can be achieved in the construction industry is by tightly integrating physical systems with their virtual representations to develop context-aware integrated analytical systems able to adapt to changes in the physical construction site/facility. Such systems bridge the virtual world with the physical world using sensors/data acquisition technologies and actuators to form closed-loop or feedback systems (Dillon et al., 2011; Chen et al., 2015). The need for feedback in construction activities has been identified by Navon and Sacks (2007) and Turkan et al. (2012).

2.1 Key features

CPS consist of two principal elements: The “physical to cyber” bridge and the “cyber to physical” bridge (Xia et al., 2011; Bordel et al., 2017). These are explained below (Fig. 1):

- Physical to cyber bridge: Construction components and processes are tracked using sensors and other tracking systems. The progress and changes in the construction process are monitored and coordinated with their associated cyber representations for further action.
- Cyber to physical bridge: This covers the actuation dimension, and dictates how the information from the sensors is used to manage the system. Actuation in this sense involves transmitting appropriate information to enable prompt decision making and/or using the captured information for active control of onsite activities, resources, or building elements.

2.2 Achieving CPS via bi-directional coordination

It is important to ensure consistency between the digital models and the physical constructed facility, which required the development of a bi-directional coordination approach to CPS (Anumba et al., 2010). Conventional integration methods only passively monitor the physical environment, while this approach facilitates tight coupling and coordination between the virtual and physical environments. Existing efforts on the development of CPS via the bi-directional approach include construction component tracking and placement (Akanmu et al., 2013; 2014), the monitoring of temporary structures (Yuan et al., 2016), and mobile crane safety and efficiency (Kan et al., 2018a). These are represented in Fig. 2.

2.3 System architecture

The system architecture shown in Fig. 3 illustrates the bi-directional coordination approach, which is based on four layers, and shows how the key enabling technologies interact to facilitate bi-directional coordination between the virtual models and their physical representations. The functions of each layer are described in the following.

2.3.1 Sensing and device layer

This layer is comprised of sensors and other data capture systems. The role of the sensors is to track different activities in the construction process or elements in the facility being constructed. For example, the real-time location sensing (RTLS) system tracks the location (or coordinates) of construction resources. The data obtained from the sensors also provides construction personnel with information needed to make control decisions (e.g., the coordinates from the RTLS can be used to track potential hazards and near misses). Other data capture systems such

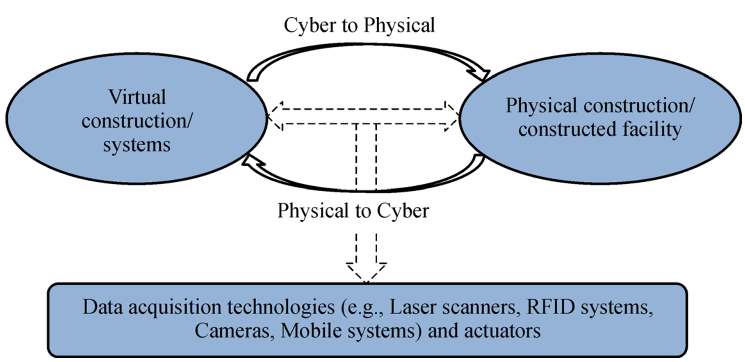

Fig. 1 Key features of cyber–physical system.

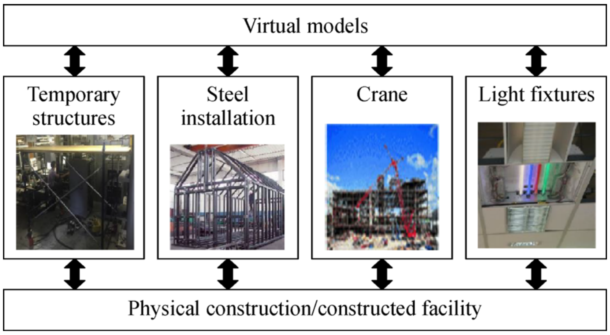

Fig. 2 Bi-directional coordination approach to cyber–physical systems.

as mobile devices can also be used by field personnel to obtain information on the status of the project. This layer provides access to data from these sources and allows for the retrieval of information via the user interface (UI).

2.3.2 Communication layer

This layer undertakes a significant amount of data processing and information transmission. It converts the raw data obtained from the sensing layer into formats that can be read by the contents and application layer. The Internet and wireless communication networks (e.g., wide and local area networks) are situated in this layer. It also connects the sensors and data capture systems to enable information exchange between field workers on site and others in the office.

2.3.3 Contents and application layer

This layer stores the raw and processed data in the local database and database server, and also enables processing of these data via control applications. The control application is dependent on the context for a given CPS application. For example, they could include machine learning algorithms that enhance the system's ability to learn. Within this layer, data from the sensing and device layer are stored and analyzed. The information stored here may include project management data (e.g., resources, cost, schedule and other information). This layer is also constantly updated with information obtained from the communication and actuation layers. 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 temporary structures.

2.3.4 Actuation layer

The actuation layer enables the following: 1) physically controlling the physical environment using actuators and 2) retrieval of important information on the basis of which decisions can be made. These can be achieved through the virtual model, which can be accessed via the UI or a mixed reality environment. Within the virtual model, users have opportunities for visualizing the effect of the sensed information (from the contents and application layer) on the system. With the UI, users can observe and track the

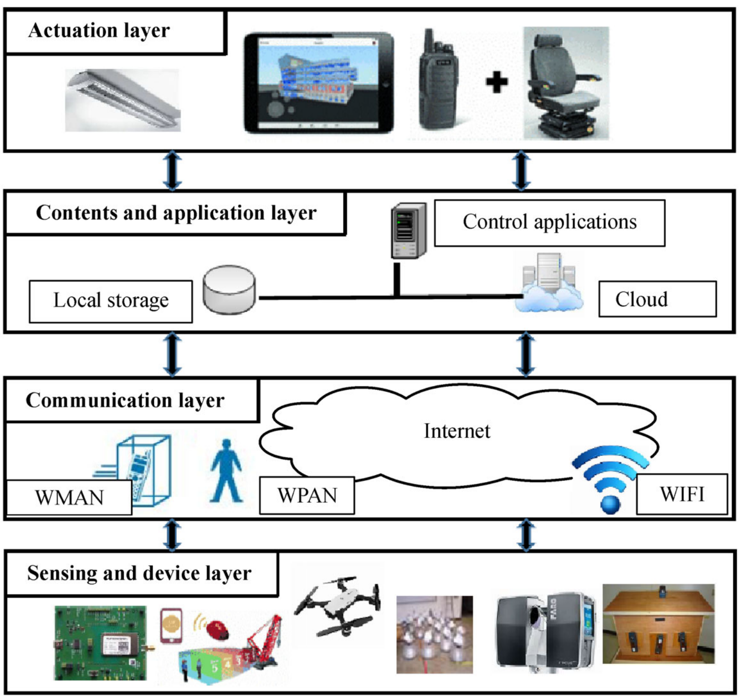

Fig. 3 System architecture for bi-directional coordination approach to CPS (based on Akanmu et al., 2013; Kan et al., 2018a).

raw and processed information from the contents and application layer. Users can also use the UI for embedding key control decisions in the virtual model which can be accessed from the sensing and device layer.

In the next three sections, the paper presents details of three different CPS prototypes that were developed for construction applications. These applications were chosen to illustrate that CPS is applicable to a variety of construction applications — component tracking and operation, temporary structures monitoring, and the safety of mobile cranes. These are sufficiently different areas to enable a broad set of lessons learned to be collated to inform future CPS development for construction applications.

3 CPS for construction component tracking and operation

The construction process requires interaction between varieties of components that, if untracked, could have implications on the performance of construction projects/constructed facilities. To illustrate how CPS can enhance bi-directional coordination between virtual models and the physical construction/constructed facility, two prototype systems have been developed. These prototype systems were designed for two types of materials: Prefabricated components (e.g., steel) and bulk materials (e.g., light fixtures), and seek to demonstrate CPS-based component tracking and operation.

3.1 Progress monitoring

For the cyber–physical system shown in Fig. 4, the constituent parts of a laboratory-scale physical building model are tagged using an RTLS system. The RTLS system, provided by Identec Solutions, is comprised of RTLS tags (i-Q350 RTLS), RTLS readers (i-PORT M 350 RTLS), satellite nodes (i-SAT 300 RTLS) and an “i-Share” position server. The i-SAT nodes interrogate and determine their distance to each of the RTLS tags. Each node communicates the distance information of each tagged part to the tags, in the form of coordinates. The coordinate of each tagged part is read from the tags by the RTLS reader and communicated wirelessly to the i-Share software. The i-Share software uses the coordinate information to compute the relative proximity of the tags. These are subsequently communicated to a Web interface from which the database is regularly updated. A plug-in, called CPSPlugin, running within Autodesk Navisworks, extracts the coordinate of each tagged part from the database and updates the status property of the virtual representation of the tagged part. Whenever there is a design change or update in any virtual part’s status property in the model,

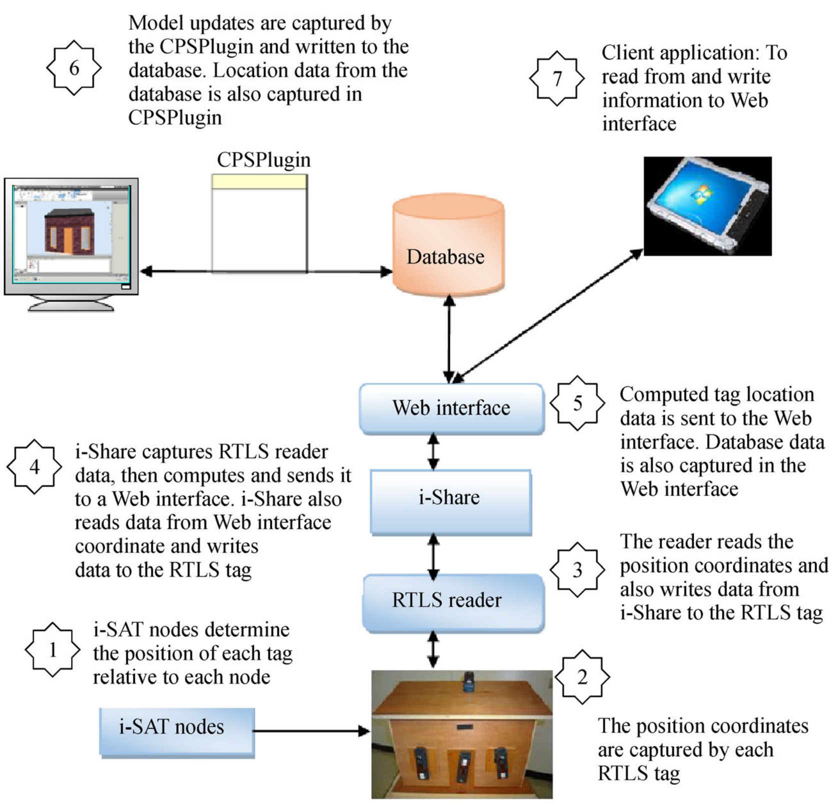

Fig. 4 Progress monitoring and as-built documentation.

CPSPlugin extracts and stores the change in the database and Web interface. From the Web interface, the change is communicated to the i-Share software, where the RTLS reader extracts and writes the information to the associated RTLS tag for access on the construction site. The field personnel can read and update the contents of RTLS tag using a client application running on the mobile device. To do this, the client connects to the Web interface, then obtains and stores the information in the database. CPSPlugin captures any status update of the tagged component from the database and initiates this within the associated virtual representation. In this application, the actuation takes place when the digital model is updated with the status information (i.e., installation status and design changes).

3.2 Bulk component tracking and control

Facility managers often have difficulties in differentiating between the locations of individual items of bulk materials (such as light fixtures), which hinders their ability to control each item. The CPS provide opportunities for locating and tracking bulk components within the constructed facility in order to improve energy management. With the CPS, physical light fixtures can be monitored and bound to their virtual counterparts in the model for monitoring and control purposes. The system is designed to interact with Tridonic System's digitally addressable lighting (DALI) system which is installed in the DALI laboratory in the Pennsylvania State University. The laboratory contains over 70 examples of state-of-the-art light fixtures, including color-changing fixtures, TV lights, spotlights, and typical commercial lighting. The Tridonic System shown in Fig. 5 includes a device server connected to three bus-masters using RS232 serial cables. The virtual lighting model of the DALI laboratory was developed using Autodesk Navisworks. It enables building occupants and facility managers to visualize the status of individual fixtures (such as installed, uninstalled, light on, light off, ballast failure, and power failure) throughout the life-cycle of the facility.

The developed prototype application performs the following functions: 1) collects the tag ID from RFID (radio frequency identification) tags attached to the light fixtures, 2) links each tag ID with the associated virtual light fixtures, 3) monitors the bus-master for control messages and signals from the fixtures and updates the virtual model, and 4) permits the control of each virtual fixture from the graphical UI of the virtual lighting. On clicking on the "Track and Bind" button in the interface shown in Fig. 6, the user can scan a tagged fixture for the tag ID. On scanning a tagged fixture, the tag ID appears in the "ID" textbox and the user can assign the tag ID to the virtual component by selecting the associated virtual

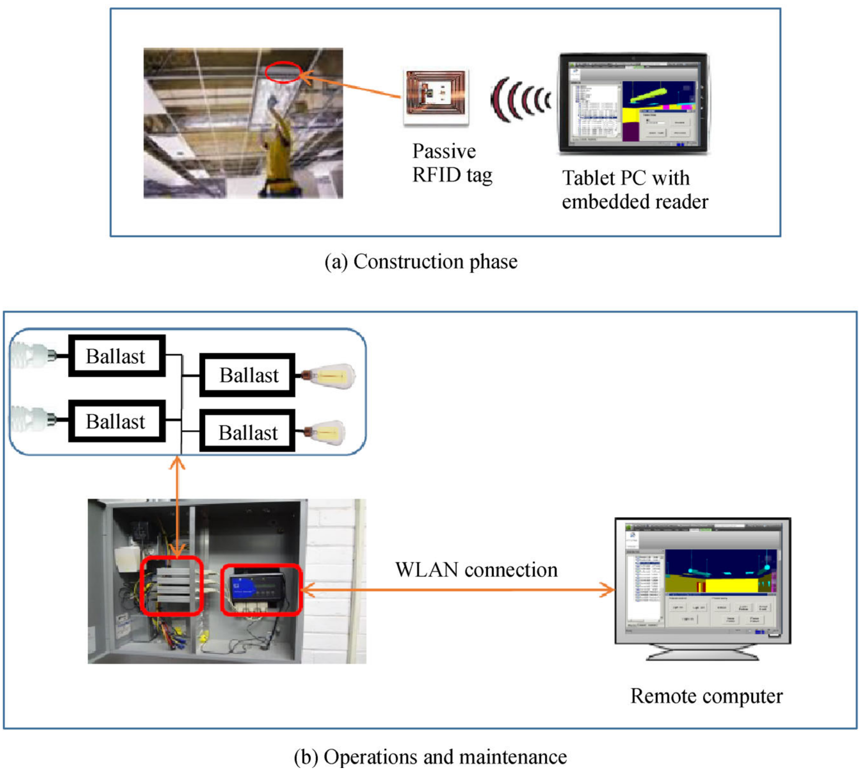

Fig. 5 Hardware setup for bulk material tracking and control (based on Akanmu et al., 2014).

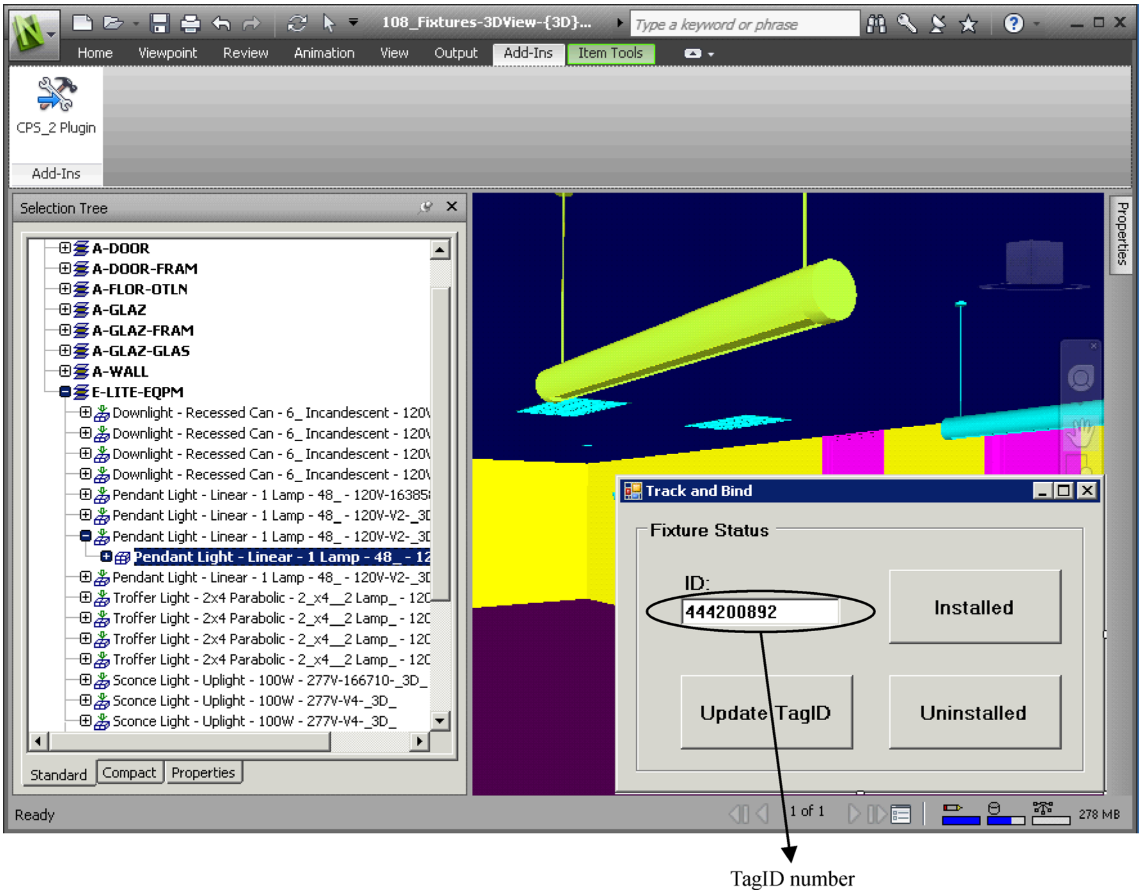

Fig. 6 Track and Bind interface with selected fixture and tag ID.

fixture from the selection tree in the model. The property tab of the selected fixture receives an update of the tag ID. The user can assign a status to the tagged fixture by clicking on the “Installed” or “Uninstalled” button.

From the interface shown in Fig. 7, users can access the progress monitoring and control system of the prototype. The interface contains buttons that represent commands for controlling the light fixtures. To control the fixtures, users need to select the name of the fixture from the selection tree within Navisworks and click on the button of the desired command on the interface. Table 1 contains a list of DALI commands and associated control messages in the form of IP addresses. The selected command button sends the IP address associated with the corresponding control message wirelessly through the device server to the bus-master. The bus-master, which serves as the actuator, interprets the IP address and controls the relevant physical fixture. The bus-master continuously monitors or listens to the light fixtures for any messages or feedback regarding their status. For example, if a lamp needs to be replaced or is turned on in the laboratory, the corresponding virtual fixture is highlighted and the status property is updated as appropriate. In situations where the fixture is defective, the maintenance manager can obtain details of the fixture from the model prior to dispatching the maintenance team for replacement.

3.3 Validation

The CPS based component tracking and operation applications were evaluated with a focus group consisting of two construction managers, three facility managers, two designers and two owners. They were selected based on their experience in the use of RFID and barcodes for project performance monitoring and preventive maintenance in constructed facilities. Overall, the participants agreed that the CPS concept of bi-directional coordination was beneficial and achieved through the applications. They suggested extending the applications to site layout management, and tracking structural components, mechanical, electrical and plumbing systems and construction equipment. The participants also provided feedback regarding 1) improvements to the usability of the client and virtual model interface, 2) Internet connectivity on remote sites, and 3) extending the CPS application to tracking other materials and exploring image-based sensing systems such as laser scanners and cameras.

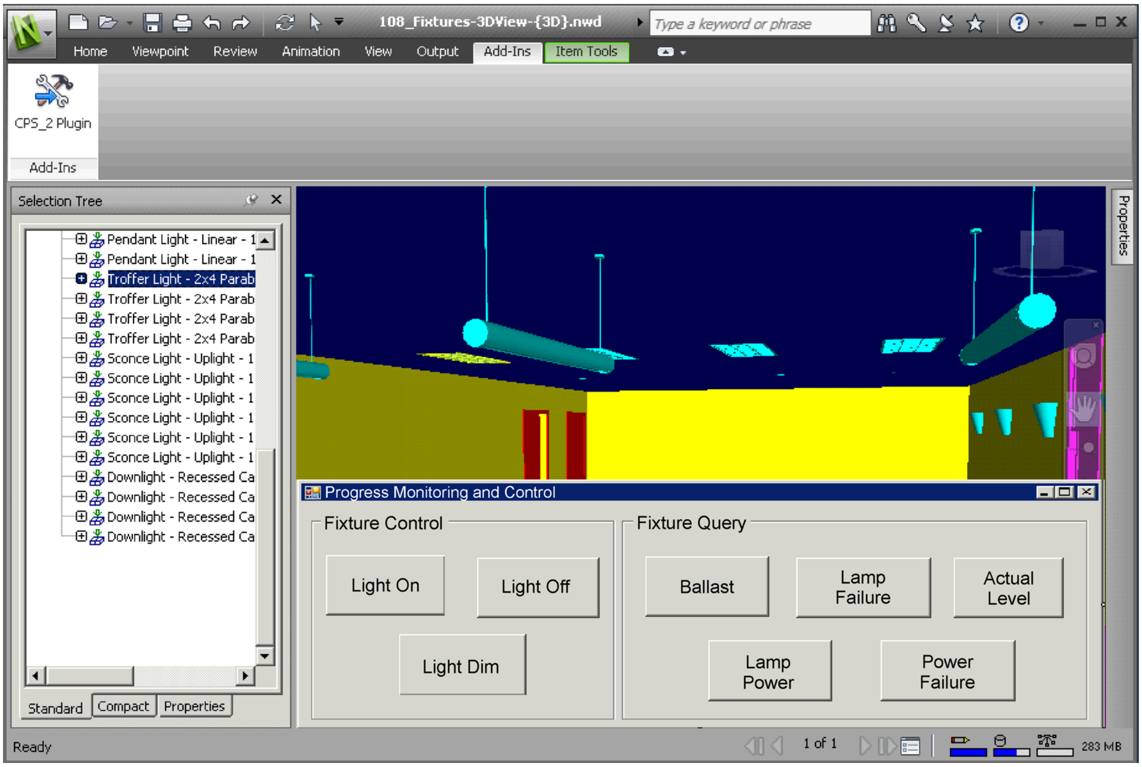

Fig. 7 Initiated interface for progress monitoring and control.

Table 1 DALI commands and messages for a sample fixture

Commands and queries	Messages
Light On	160, 0, 0, 0, 11, 5, 174
Light Off	160, 0, 0, 0, 11, 6, 173
Light Dim	160, 0, 0, 0, 11, 0, 171
Actual Level	0, 0, 0, 0, 11, 145, 154
Ballast	0, 0, 0, 0, 11, 160, 171
Lamp Failure	0, 0, 0, 0, 11, 146, 153
Power Failure	0, 0, 0, 0, 11, 155, 144

4 CPS for temporary structures monitoring

To demonstrate the applicability of CPS to an aspect of construction that is often neglected, it was decided to explore the monitoring of temporary structures. These are generally the structures that provide temporary support during construction or are used for a short period (Grant and Pallett, 2012). In this section, they refer to the temporary structures used in the area of architectural engineering to support construction work. Examples of these include temporary bracing, temporary sheeting, formwork systems, scaffolds, underpinning works and temporarily used structures.

Over the years, numerous accidents have resulted from improper management of temporary structures. However, very little attention has been paid to address this issue. For example, an average of 20 cave-in accidents occurred annually causing fatal injuries from 2006 to 2012, which was even worse with an annual average of 40 fatal cave-in accidents from 1992 to 2006 (Bureau of Labor Statistics, 2018).

Currently, in the US, only a limited amount of regulation (e.g., Occupational Safety and Health Administration (OSHA) – Standards-29CFR and the Code of Federal Regulations – CFR 1926.706(b)) has been published for the safe management of temporary structures. These regulations cover only a few types of structures and leave the management of the rest unregulated. To supplement these safety regulations, industry practice and safety training programs have been adopted. For example, as recommended in the OSHA regulation, employers are responsible for providing safety training and education programs to their employees. OSHA and local governments also provide safety training resources online, including excavation safety training, fall protection, scaffolding, concrete, and masonry.

However, these conventional methods (including safety regulation, industry practice, and safety training) for temporary structures fail to fully cover the temporary structures, such as the lack of safety regulation on temporary performance stages (Mckiniley, 2011). Even with full coverage by the safety requirements for all the temporary structures, construction workers tend to work under high pressure, which makes working with caution very difficult for them (Fabiano et al., 2008). More technically advanced methods are needed and that is the focus of the CPS system described below.

4.1 Temporary structures monitoring (TSM) — a CPS approach

Recent research achievements have indicated the potential benefits of CPS for advanced tracking of temporary structures. For example, there have been research efforts in applying CPS enabling technologies (such as BIM) to temporary structures monitoring. These have raised the prospects for CPS in advanced tracking and control of temporary support systems and short-term stages for theatrical and other performances.

In light of the above, a CPS approach is designed for better safety monitoring of temporary structures, with scaffolding used as an example. In general, a CPS approach for temporary structures monitoring requires bi-directional coordination between the temporary structures and their virtual representations, as shown in Section 2 of this paper. Such an approach relies on three major components, including a digital model, a physical structure, and the information bridge supported by CPS enabling technologies. As the information bridge connects the virtual and real worlds (see Fig. 8), information can be exchanged frequently. This supports frequent updates on the temporary structural status as well as safety instructions from the safety professionals.

4.2 Introduction to TSM prototype system

The TSM prototype system was designed and built in accordance with the system architecture shown in Fig. 3. The UI of such a prototype system was developed in Autodesk Navisworks (Fig. 9), which provides a virtual model interface to the physical temporary structures. As for the information exchange, three major tools are used: Sensors (to collect structural information from the real world), on-cloud database (to store structural information collected from sensors and instruction information from the virtual models), and the application programming interface (API, installed on portable devices for easy communication with the construction workers). It should be noted that while CPS supports the use of actuators for direct monitoring, human interaction is critical for hazard control. This is because the construction jobsite is complex and any structural changes should be carefully reviewed and determined by the professionals. Besides, without warning or notification, sudden and unexpected movement by the actuators may cause potential safety problems for the construction workers. Therefore, the actuation component of TSM is designed to be based on human notification and action.

The TSM prototype system is designed to work such that: 1) structural information (including the degree of inclination and disconnection signal) of the physical temporary structures is obtained through the attached sensors and calibrated; 2) based on the updated structural information, the virtual platform continuously checks the safety status of the real structure; 3) when potential hazards are detected, alerts are sent to the field workers and safety managers using mobile devices; and 4) end-users correct structural deficiencies when they receive the warnings. Through this continuous remote monitoring of the temporary scaffolding structure, the TSM is able to prevent potential structural failure.

4.3 TSM prototype system test and evaluation

Laboratory experimental test has been conducted for system evaluation of the TSM prototype. As base settlement has been highlighted as a major concern by Whitaker et al. (2003) for accidents involving scaffolding systems, the TSM prototype system was tested by simulating a base settlement scenario. It was observed that as the base settlement of scaffolding system reaches certain safety threshold, the TSM system identified this potential issue immediately by highlighting the virtual component in question with alarming color and sending the warning message to the portable devices. By tapping the warning message on the portable devices, users can see clearly the location of the potential issue through an image

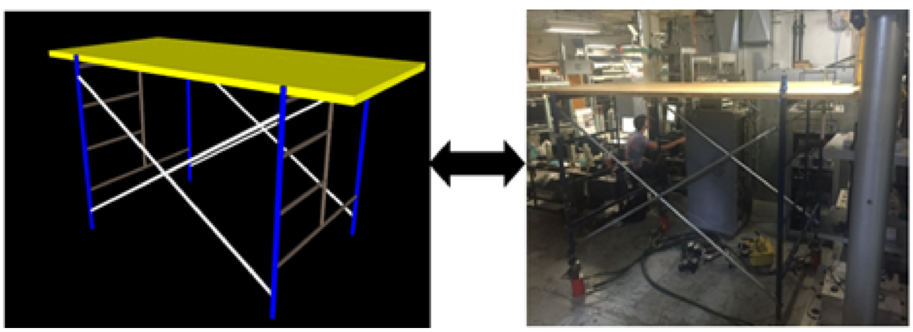

Fig. 8 Virtual and physical temporary structures.

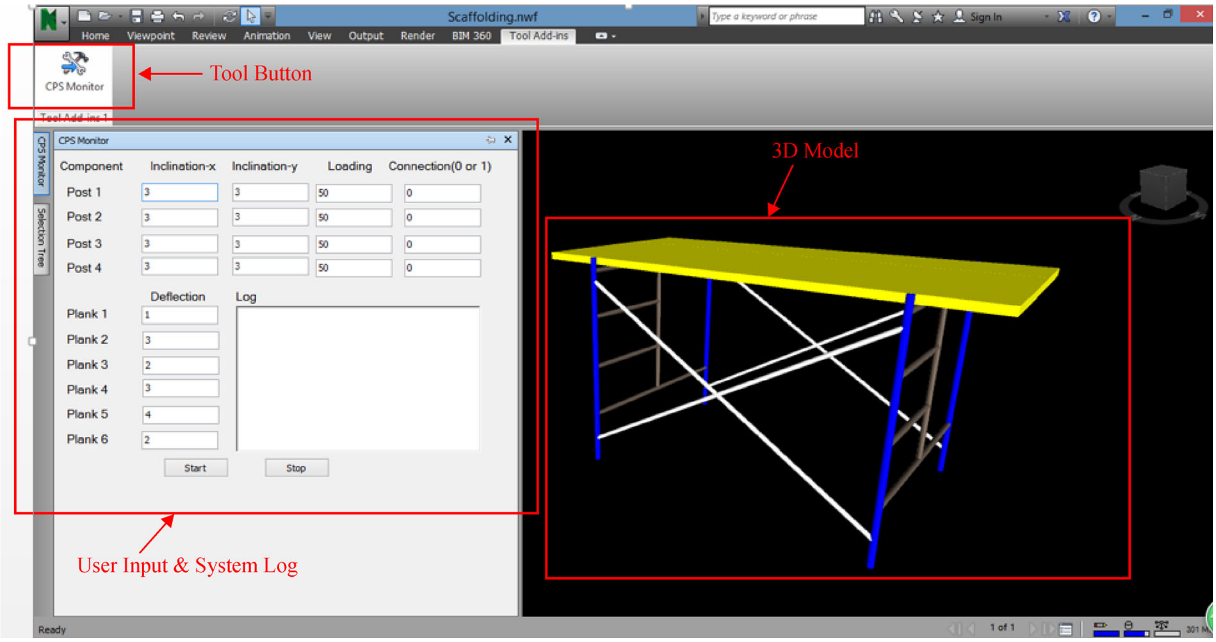

Fig. 9 User interface of TSM system.

of the virtual model and the potential structural problem identified by TSM. The experimental test result indicates that TSM works effectively in identifying potential structural hazards. It responds to the structural hazards accurately and immediately by providing valuable information to the users.

In addition, an evaluation workshop has been held with 15 experts experienced in the erection of temporary structures. The evaluators considered the TSM as useful in monitoring scaffolding system with reliable warning information. They felt that it provides a very helpful means of improving the safety of temporary structures.

Both the experimental test and the evaluation workshop indicate that CPS is critical to the development of an advanced temporary structural monitoring system. In particular, the CPS approach enables remote monitoring of the structures in the real world. Furthermore, the information exchange between the virtual and real world enables the visualization of the potential problems of temporary structures.

5 CPS for mobile crane safety

Following the CPS used for new construction and temporary structures monitoring, it was considered important to explore how CPS can improve the use of plant and equipment on construction sites. Cranes, which are extensively used for performing lifting operations on construction sites, were considered a suitable application area. In fact, the numbers of accidents caused by the operation of cranes are disproportionately high. It was reported that crane-related accidents account for up to one-third of the total accidents that take place on construction sites (Neitzel et al., 2001). More attention should be paid to such accidents since they result in severe consequences such as occupational fatalities and catastrophic destruction of the surrounding area.

Among all types of cranes, mobile cranes have quite distinct uses. They hoist and transport various materials to their assigned lifting location, and usually share the working environment with various operations. Compared to other types of cranes, mobile cranes are more dynamic and flexible in undertaking lifting operations. According to Kan et al. (2018b), mobile crane-related fatalities totaled 325 in the US construction industry from 2006 to 2016, accounting for 56% of the crane-related fatalities. Typical mobile crane-related accidents include electrocution, crane tip-over, and struck by crane parts or load (Kan et al., 2018b). One of the determining causes of these accidents is the operator's lack of visibility of the crane itself and the surrounding environment (Hinze and Teizer, 2011). While performing the lifting operations, crane operators mainly rely on hand gestures or audio instructions from the signal person. They receive limited visual information on their operating environment and the objects to be lifted. In this context, monitoring mobile crane operations and providing enriched information to the crane operator are of vital importance. These are critical first steps toward identifying and mitigating potential mobile crane-related hazards on construction sites.

To provide real-time pro-active safety assistance for mobile crane operations, a CPS-based approach to monitoring mobile crane operations in real-time and providing control feedbacks to the crane operator was proposed. Using the system architecture shown in Fig. 3, a framework has been developed to enable the development of the CPS-based approach, as shown in Fig. 10. The framework outlines the key tasks for enabling the bi-directional information flow between the physical operations and their virtual representations. The proposed CPS-based approach was developed and evaluated based on the operation of a 300-ton crawler crane. The following subsections demonstrate the processes for developing the CPS-based approach and the details concerning each task.

5.1 Crane pose sensing

The proposed approach comprises two aspects, namely real-time monitoring and control feedback. Real-time tracking of mobile crane operations allows for the ongoing crane operation data to be captured and transmitted to the virtual platform. The first and most critical aspect of monitoring mobile crane operations is to sense crane poses. To accurately sense crane poses, several critical motions need to be taken into consideration, including 1) boom length, 2) boom slew angle, 3) boom lift angle, and 4) payload state. A sensing system consisting of different sensors was used to capture these critical motions. Figure 11 illustrates the deployment of the sensing system. The sensing system adopted in this study was developed for a lattice boom crawler crane, but is applicable, with minimal adaptation to other types of mobile cranes. More details can be found in Kan et al. (2020).

5.2 Work environment recognition

In enhancing mobile crane safety, it is very important to enhance the operator's situational awareness (Fang et al., 2018). The operator's visibility and awareness of the work environment needs to be maximized. Thus, in addition to sensing crane poses, it is of equal importance to recognize the objects in the work environment that could interfere with the mobile crane's operations. A sensing and instrumentation system comprised of various types of sensors was leveraged on key objects components within the crane's operational area such as workers and material stacks. In addition to such objects, the mobility of the mobile crane should also be taken into consideration. While moving to its assigned lifting position as a whole entity, the location of the crane on-site can also be captured through the sensing systems shown in Fig. 12. Details concerning the sensors adopted and their functionalities can be found in Kan et al. (2020).

5.3 Sensor data conversion for lifting scene reconstruction

Once the crane's motions and the surrounding site

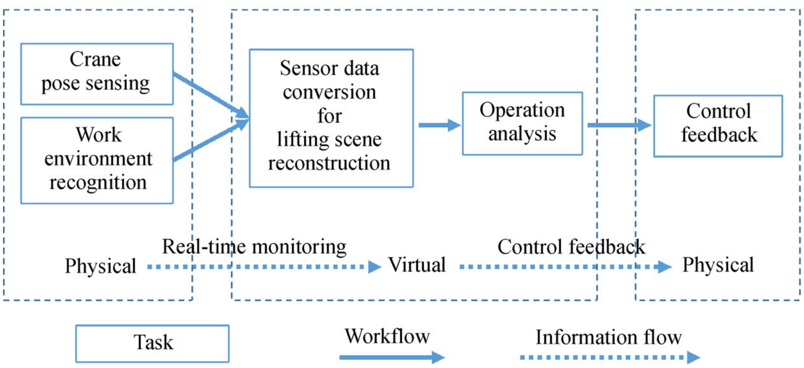

Fig. 10 CPS framework for mobile crane safety.

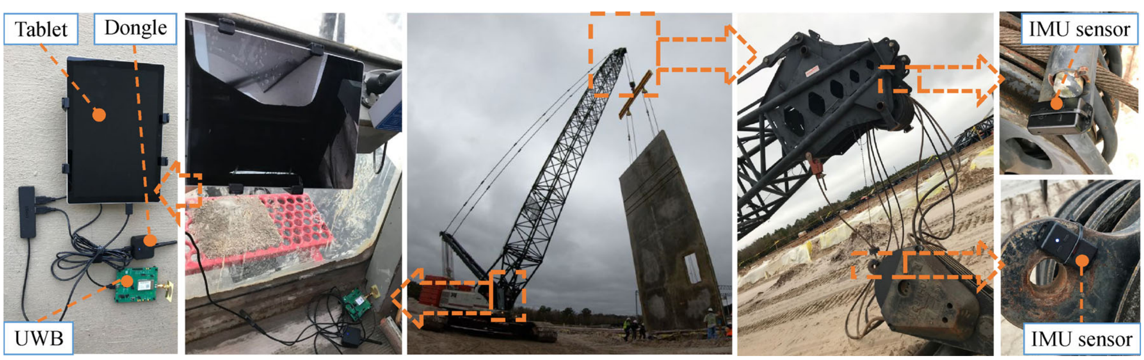

Fig. 11 Sensing system deployment for crane pose sensing (UWB: ultra-wide band, IMU: inertial measurement unit).

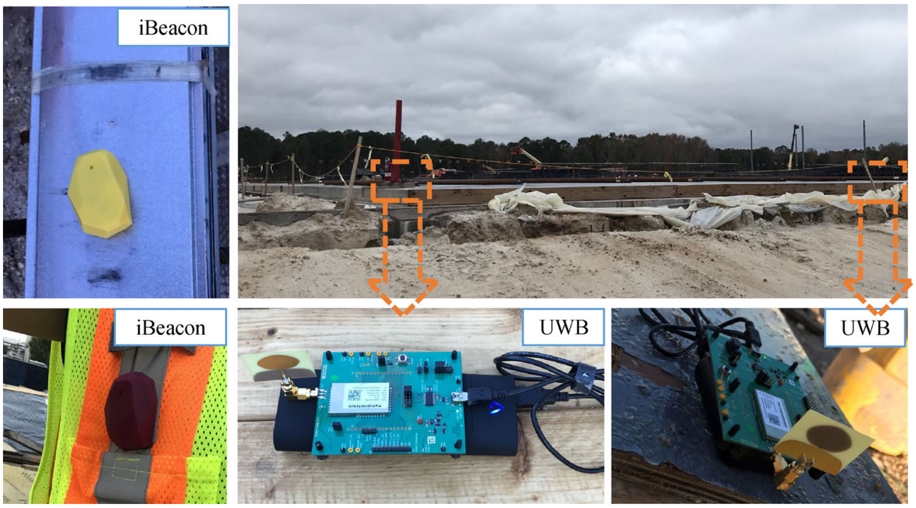

Fig. 12 Sensing system deployment for work environment recognition.

environment are captured through the sensing systems, the data are converted to reconstruct the crane lifting scene in real-time on a pre-developed virtual platform. Variations in the crane pose and within the operational area are also updated in the platform. The development of the virtual platform is presented in Kan et al. (2018a). Figure 13 shows the reconstruction results by utilizing the data collected by the sensing systems shown in Figs. 11 and 12. The top portion of Fig. 13 shows the screenshots of the actual lifting from the time-stamped video captured on-site using a camera, while the bottom portion illustrates the simultaneously reconstructed crane lifting scenes based on the recordings made in the virtual platform.

According to the time-stamped video captured, a one-second latency was identified between the reconstructed and the actual lifting scene. This is primarily because the sensory data transmission was via Bluetooth and there is an inherent delay with the wireless Bluetooth connection. In addition, data processing in the virtual platform can also be held accountable for the latency.

5.4 Operation analysis

Potential safety hazards are identified after crane motions and updates within the operational area have been reconstructed. Hazards that have the potential to cause mobile crane-related accidents were identified from a study of incidents recorded on the OSHA website. Appropriate safety rules obtained from OSHA citations are embedded in the virtual platform to gauge the safety condition of the mobile crane. When a potential hazard emerges during the crane operations, the virtual platform provides timely control feedbacks.

5.5 Control feedback

The provision of control feedback is the last task in implementing the CPS-based approach. It also completes the bi-directional information flow loop — from the cyberspace back to the physical world. Once potential hazards appear, control feedbacks are initiated with alerts

Fig. 13 Crane operations on site (top) vs. reconstructed crane operations in a virtual platform (bottom) (based on Kan et al., 2020).

pushed to the crane operator, as visual and audio cues. Visual cues provide rich information such as visual data and timely alerts using a tablet computer mounted in the operator's cabin, as shown in Fig. 14. A UI is designed to show the reconstructed motions of the crane, the crane's operational area, and appropriate warnings with supporting audio as needed. The UI shown in Fig. 15 displays the reconstructed crane lifting operations within the operational environment. Identified hazards are also highlighted to the operator, with warning sounds. Figure 15 shows the detection of the worker tagged with an iBeacon sensor within the 15 feet safety clearance. Also displayed is information on the appropriate safe distance, actual distance, as well as the closest part of the crane.

During this on-site experiment, the sensory data captured was routinely recorded in a .txt file for detailed analysis. A site camera was deployed around the crane to record the actual lifting scene. The outcomes of reconstructing the crane lifting scene were validated through comparative analysis of the time-stamped video obtained from the site camera with the simultaneous reconstruction of the crane lifting scene from the virtual platform. Surveys were also conducted with the crane operator to evaluate safety improvements by incorporating the CPS-based system.

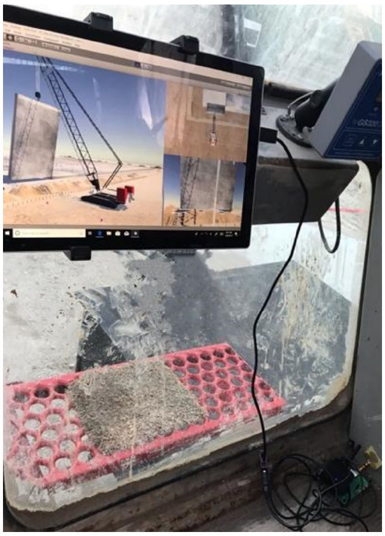

Fig. 14 Tablet deployed in the crane cabin for displaying control feedbacks.

From the above experiments, it can be seen that the CPS-based approach has the capacity to considerably enhance the safety of mobile cranes. Through bi-directional communication between the crane operations and the associated digital representations, the prototype system proffers numerous benefits in proactively tracking crane operations, sending enriched control feedbacks to the crane operator, allowing timely and informed decision-making and, ultimately, reducing significantly the number of accidents that can be ascribed to mobile cranes.

6 Discussion

Successful construction projects are delivered timely, safely and consistent with the as-planned or designed models. The resulting as-built model is critical for monitoring and controlling the performance of buildings and their key components (such as light fixtures). The CPS applications described in this paper show how these benefits can be achieved. The applications relate to 1) tracking and controlling the assembly and condition of building components during the construction and facility management phases of buildings, 2) monitoring the performance of temporary structures and addressing potential structural deficiencies, and 3) enhancing the safety of mobile crane operations on construction sites. The development of the CPS for construction applications

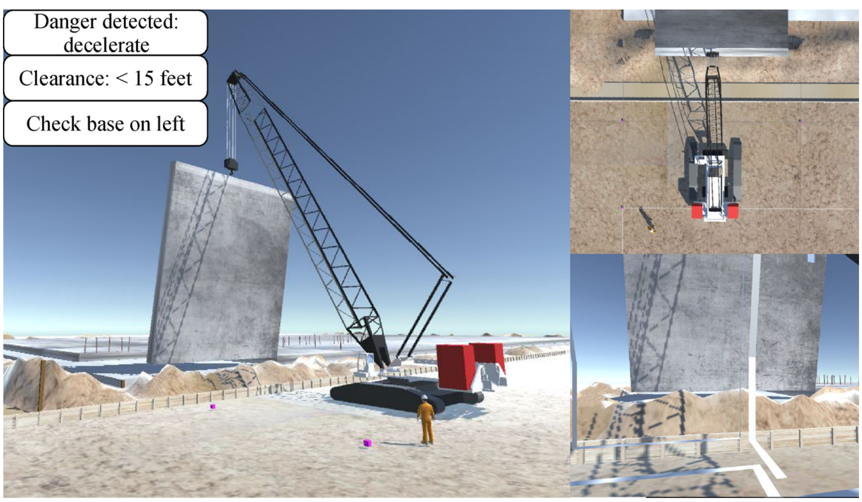

Fig. 15 User interface for lifting scene visualization and potential hazard identification.

have been useful in demonstrating the applicability of the technology to the construction industry. Some of the lessons learned from these three systems are briefly discussed below, which is followed by a brief exploration of what the future holds for CPS in construction.

6.1 Lessons learned

Several lessons were learned from the design and implementation of the prototype CPS applications described above. Specifically, these lessons were encountered when deciding on the following: 1) problems that can be addressed with CPS, 2) most suitable sensing systems to address the problems, 3) how to assemble the key technologies and techniques to develop a laboratory-scale prototype of the CPS applications, and 4) how to implement the laboratory scale prototypes in the field. The lessons outlined below cut across the individual applications and are intended to guide others seeking to deploy CPS in other areas of construction:

- Not all problems can be addressed with CPS. Detailed knowledge of the construction issue being addressed is very important in deciding whether or not CPS is the most appropriate solution. Some of the triggers for CPS application in construction have been suggested by Akanmu et al. (2013);
- The use of accurate and current virtual models is very important for ensuring bi-directional consistency between the physical elements and their corresponding cyber representations. For example, in the component tracking and operation application, changes made during the project need to be documented in the virtual models so that progress updates from the construction site can be a true reflection of the as-built model;
- One of the triggers for applying CPS to construction is to enhance the monitoring and control of activities. For this to occur, there needs to be tight integration and consistency between the digital model and the on-site construction. Therefore, the bi-directional coordination mechanism is a critical component of developing and deploying CPS in construction and its design needs to be thoughtfully undertaken. When this is not the case, the association between the cyber elements and their physical counterparts will be loose and sub-optimal. This could have downstream implications on the safety of workers (e.g., in the case of equipment monitoring and control);
- Commercially available sensing technologies offer different levels of support to CPS applications. Developers of CPS systems need to choose, for each specific application, the best sensors for capturing and transmitting the requisite data to and from the physical elements. Details will be based on the application domain, the other components of the system development environment (hardware, software, middleware, etc.), and the extent to which the sensors can be enhanced to address the sensing requirements of the CPS application;
- All the applications presented in this paper were experimented within the laboratory prior to field deployment. Laboratory experimentation of this type is critical for determining the effectiveness of the prototypes before they are deployed on an actual construction site. This also enables a distinction to be made between problems emanating from design deficiencies and those associated with the specifics of the site;
- Moving from laboratory-scale prototypes to site deployment is not a trivial process, as numerous practicalities need to be taken into account. Some of these are: How scalable the prototypes are, and economics, power supply, potential for wireless systems, site personnel, construction equipment/vehicles, etc. Careful consideration needs to be given to these and the prototypes should be refined to enhance their utility.

6.2 Future directions for CPS in construction

The future of CPS deployment in construction will be governed by numerous factors. However, this paper will focus on the evolution of technology and the advent of new application areas, as these will have the most significant influence.

6.2.1 Evolution of technology

Technology is constantly evolving and offers new opportunities in many fields. Those technologies that will have a major impact in the construction domain are: Context-awareness, drones, 3D printing, cloud computing, non-volatile memory, mobile communications, sensing, Internet of Things (IoT), and artificial intelligence (AI).

The advent of context-aware computing means that applications can be tailored to provide context-specific information, operations and services to their end-user (Zhou et al., 2011). As the context in the physical environment changes, this can be detected by sensors, with the information being automatically transmitted to the associated virtual model for relevant and timely action to be taken.

Drones (or unmanned aerial vehicles, UAV) are continuing to grow in use in the construction industry. Their use in CPS applications offers tremendous opportunities, as they can be used to instigate actions and obtain data/information from both the physical and virtual environments (Mutter et al., 2011; Selecký et al., 2017), which makes them highly effective as a bi-directional communication mechanism between the construction components and their digital representations. This offers considerable benefits in places with limited accessibility for site personnel (e.g., problematic temporary structures or defective building envelope systems), and in situations that require digital images to record environmental deviations. The use of UAV as potential carriers of component-based sensing systems such as real-time location sensors can also facilitate future CPS applications. UAV can be used to tag construction resources and reconfigure the placement of sensors based on the type of activity taking place and resources to be tracked.

3D printing is a quintessential type of CPS given that it takes a digital representation as input and uses this to produce a physical artifact. Consistency between the printed artifact and its digital model can be perpetuated by embedding sensors in the artifact, thereby making it possible for the artifact to be actively controlled from the virtual model. The ability to quickly develop physical prototypes of proposed CPS concepts will also enhance laboratory experimentation, which is critical for identifying potential issues in preparation for field deployment.

With cloud computing, software systems, services and data can be based in the "cloud", making it possible for end-users to quickly and efficiently avail themselves of access to a variety of tools and services, without having huge costs associated with owning and maintaining these and the associated storage issues. Leveraging this will facilitate the development of economical CPS for a conservative industry, which is particularly important to facilitate future CPS models that will largely be built from aggregated construction data.

As non-volatile memory continues to become more economical, it is envisaged that sensors and other data acquisition systems will have greater capacity for more secure and durable storage of data and information. This will also enhance the data/information transmission between virtual models and sensors placed on physical components.

Developments in mobile communications systems, particularly the advent of 5G communication networks and their successors, will greatly facilitate the effective and efficient transmission of data/information across discrete applications and between geographically dispersed construction project personnel. It will also be much easier to make connections among wireless and wired sensors, devices and systems, thereby facilitating CPS deployment in many situations.

Sensing is one of the fastest developing areas in computing as well as in terms of its application to the construction industry. There is growing diversity and sophistication in the types, range, capacity, memory, durability, utility and interdependence of sensors. This means that considerable skill is needed in the design of sensing and instrumentation systems to leverage this versatility to accomplish the task at hand. It also means that their utility in situations where active control is required will be greatly enhanced, as they interface with both the physical components and their virtual replicas. This will considerably enhance the utility of future CPS systems.

There is a growing recognition of the potential of IoT in many industries, with construction now beginning to conduct a number of trials (Lee, 2017; Tang et al., 2019). Integrating numerous physical construction components within an IoT system opens up interesting opportunities for enhancing the effectiveness of any cyber–physical system that the same components are part of. One can envision future IoT-based construction site environments where workers and equipment are networked to interactively and collaboratively share location information and resources. Potential accidents, fatalities, near-misses, and close-calls could be detected before they occur.

The re-emergence of AI is highly promising for CPS-based construction applications. AI-based CPS applications have the potential to utilize intelligent data analytics, machine learning, and other advanced techniques to enhance the bi-directional coordination between the computational resources and the physical environment, and to inform both human decision-making and process automation. Applying AI to existing data from past construction projects and data harvested from sensing systems will make future CPS more intelligent and responsive to uncertainties and failures.

Most of the above technologies are in existence but have only had marginal adoption in the design and implementation of CPS-based construction systems. As technology evolves, more opportunities will become available for leveraging them in this domain.

6.2.2 Advent of new construction applications

The advent of new application areas for CPS in construction is critical for determining the level of impact that it will have on the industry. Emerging application areas include, but are not limited to, the following.

The light fixtures application described earlier in this paper is illustrative of the potential for CPS deployment in the management of constructed facilities. As shown with the light fixtures, the status of the physical components can be actively monitored and controlled from the cyber environment. The area of open CPS (where computing systems interact with physical systems) for capturing and incorporating the social aspects of building use and maintenance in the design of maintainable buildings is another facility management (FM) application area. As more FM departments and building occupants communicate how they engage with buildings on social media, opportunities exist to leverage machine learning algorithms to mine information on building defects, defective components, utilization rates, time-space conflicts, livability of spaces, and occupant wellbeing. The data generated would be useful for generating FM rules for improving design platforms for maintainability. The resulting maintainable buildings can be classed as open CPS.

Smart cities and communities, in which a large number of information and communication systems are utilized to facilitate the connection between community residents and their surrounding environments, is a ripe application area for CPS deployment. With the increasing growth in urban areas, reducing congestion and increasing public safety are essential in smart cities and communities. This application area provides the opportunity for improved coordination of critical infrastructure systems in cities such that they could function more efficiently and economically.

Improvement of worker's physical abilities in safe work performance is another application area for CPS. There is an increase in the rate of musculoskeletal disorders among construction workers. Workers can be trained in virtual reality while they interact with physical tangible construction resources. By tracking their tangible interaction in a virtual environment, training materials could be selectively provided to control or improve their physical ability for performing work with safe postures.

Infrastructure systems are increasingly interdependent in the delivery of products and services. These dependencies can trigger vulnerabilities that could result in cascading failures among these infrastructure systems. Addressing this issue with CPS necessitates thorough understanding of the nature and extent of these interdependencies between infrastructure systems. Opportunities offered by machine learning will enable existing data (and real-time data obtained from sensing systems) about the dependencies of infrastructure systems to be modeled. Such models could be leveraged for investigating alternative designs and materials for improving the resilience of infrastructure systems.

District-scale energy management is now recognized as offering the opportunity for the supply and demand aspects of energy to be at a higher level than individual buildings. This requires the ability for energy utilization to be monitored physically using appropriate sensors and other data capture technologies that are linked to a district level digital model making real-time optimal decisions on the type and capacity of energy being distributed to a given district. In addition to exploiting CPS technology, the energy management could also incorporate elements of context-awareness.

A new domain of CPS application is in what can be referred to as "content-aware constructed facilities", which are intelligent enough to know their contents such as fixtures, fittings, equipment or occupants. This knowledge of content information is invaluable in healthcare environments where it will enable critical equipment, healthcare workers and other items to be tracked in real-time from a digital facility model, with appropriate messages being sent or other control instructions being activated (e.g., personnel can be sent specific instructions on emergencies or equipment can beep or light up).

7 Summary and conclusions

This paper has sought to describe the development of cyber–physical systems for construction applications. It has demonstrated CPS applicability to a variety of application areas, each of which addresses a real problem in the construction process. The lessons learned in the development of these CPS applications and the potential future trajectory of CPS development for construction are also discussed in detail. The benefits that CPS offer to construction include the following:

- Real-time exchange of information between office-based designers and construction site-based personnel;
- Reduction of construction risks with more efficient tracking and control of activities and processes;
- The creation of up-to-date as-built models, which can be utilized during the facility's operation, maintenance and decommissioning phases;
- Potential for active control of physical elements during the operation and maintenance stages of the facility's life;
- More hypothetical scenarios can be explored and corresponding action plans can be formulated;
- Potential for the integration of more sustainability principles into the construction process;
- Construction safety can be enhanced by foreseeing and proactively dealing with potential hazards;
- There will be more improvements based on being able to monitor processes as they happen, and being able to manipulate components from the virtual model.

With continuing evolution of technology and new domains for CPS deployment in construction, the potential of CPS is likely to be strong for the foreseeable future. As such, construction organizations have to make the necessary investments to ensure that they are well placed to take advantage of this.

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