REVIEW OF THE POTENTIAL FOR A CYBER-PHYSICAL SYSTEM APPROACH TO TEMPORARY STRUCTURES MONITORING

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Abstract

Around three quarters of construction workers work on or near temporary structures, whose failures lead to more than 100 deaths, 4500 injuries, and damage costing $90 million each year in the United States. However, few of the temporary structural problems have been well addressed, especially when compared with the increasing improvements in permanent structures. Meanwhile, the review of leading causes of temporary structural failures identifies the need for improved methods, such as Cyber-Physical Systems (CPS), to prevent potential structural hazards. This paper makes the first effort to examine CPS applicability in temporary structures, and potential benefits brought by CPS to temporary structural monitoring. Key definitions and features of CPS, CPS applications in both other industry sectors and the built environment, and applications of CPS enabling technologies in temporary structures are reviewed. It is concluded that CPS provides opportunity to address safety and structural problems of temporary structures. For a clear understanding of how CPS works in structural monitoring, an application scenario of scaffolding system is presented. Finally, system requirements followed by a system architecture are identified.

Keywords: Cyber-Physical Systems, temporary structural monitoring, system architecture

INTRODUCTION

The construction industry has had a long-standing record of poor productivity (Park et al. 2005), safety hazards (Mohamed 2002), financial waste (Shane et al. 2009), and schedule delays (Shi et al. 2001). Some of these problems, like occupational injuries, quality of structure, and speed of construction project, are affected by temporary structures (i.e. scaffolding, temporary support system, and formwork system) (Fabiano et al. 2008). To be specific, it is estimated that three quarters of the construction workers in the United States work on or near temporary structures (OSHA 2014). The improper management of temporary structures results in 100 deaths, 4500 injuries, and costs $90 million every year (BLS 2013).

The term ‘temporary structures’ refers to systems and assemblies used for temporary support or bracing of permanent work during construction, and structures built for temporary use. The former are defined as the elements of civil engineering work, which support or enable the permanent works (Grant and Pallett 2012). Included are temporary support systems such as earthwork sheeting and shoring, temporary bracing, soil backfill for underground walls, formwork systems, scaffolding, and underpinning of foundations. The second category includes temporary or emergency shelters, public art projects, lateral earth retaining structures in construction zones, construction access barriers, temporary grandstands and bleachers, and indoor and outdoor theatrical stages (Parfitt 2009).

The last four decades have seen numerous collapses related to improper erection and monitoring of temporary structures. In 1973, the improper removal of forms triggered a progressive collapse of the Skyline Plaza (Bailey’s Crossroads, VA), killing 14 construction workers and injuring 34 others (Feld and Carper 1997). Another example was the collapse of a
Section of the University of Washington football stadium expansion in 1987 due to premature removal of temporary guy wires (Feld and Carper 1997). A major scaffold system on a 49-story building on 43rd street in New York’s Time Square collapsed in 1998 as a result of bracing removal, resulting in the death of one individual, several injuries and hundreds displaced from their residences (Stewart 2010).

Considerable efforts have been made to prevent temporary structural failures, including safety regulations on the design, installation, maintenance, and dismantling of temporary structures, safety training programs required by government, and case studies of serious temporary structural failures. However, there are still some temporary structures, such as indoor and outdoor theatrical stages, which are not covered by any safety regulations (Mckiniley 2011). Besides, even with enough safety regulations and training programs, the temporary structural failures cannot be fully prevented as the workers tend to work under great pressure and make mistakes unconsciously (Fabiano, et al. 2008). For automatic and continuous monitoring of temporary structural integrity regardless of causations, an intelligent temporary structural monitoring system, which can track and monitor the temporary structural performance, is in high demand (Jung 2014).

Recent developments in information and communication technologies, such as data acquisition system (DAQ), Building Information Modeling (BIM) and CPS applications in improved structural health monitoring, provide the potential for improved temporary structures monitoring. The use of CPS offers an opportunity for changes in the physical structure to be captured and reflected in a virtual model. Conversely, changes in the virtual model can be communicated to DAQ embedded or attached to the physical components. This bi-directional coordination between physical and virtual systems enables the temporary structures to be continuously monitored and assessed for performance in order that potential hazards can be identified and addressed prior to an accident, irrespective of causation.

This paper proposes and analyzes the potential for a CPS approach to temporary structures monitoring. First, the key definitions and features of CPS are summarized for a better understanding and its potential benefits. Second, CPS applications in other industry sectors and in the built environment are reviewed to identify current research limitations and explore CPS applicability in temporary structures. Third, potential areas for CPS applications in temporary structures are identified, including both temporary performance stages and temporary support systems. According to previous analyses, the potential benefits and barriers, as well as an application scenario in temporary structures monitoring are presented. Finally, based on the identification of system requirements, the system architecture is designed as an example for CPS approach to temporary structures monitoring.

**RESEARCH METHODOLOGY**

This paper presents the findings of the on-going applications of CPS in various industry sectors, and the critical issues to be addressed for temporary structures with an aim to identify CPS applicability to temporary structures. Due to the objectives, the research methodologies adopted for this study include literature review, scenario development and validation, and expert interview. The literature review was conducted to identify the potential opportunities, approaches and benefits offered by CPS to temporary structures, and the system requirements. The urgent need for enhanced management of temporary structures is also reviewed. An application scenario to temporary structures was developed and validated as an example of how the temporary structures may be better monitored. Finally, the expert interview was conducted to validate the identified system requirements, which assists in the system architecture design of CPS for temporary structures monitoring.

**OVERVIEW OF CPS**
Due to their different research scopes, researchers view CPS in different ways. A better understanding of its definition and key features is helpful in the identification of potential benefits and barriers to CPS application in temporary structures.

Key definitions of CPS
Several researchers have defined CPS as follows:

- **Cyber-Physical Systems** are smart systems that have cyber technologies, both hardware and software, deeply embedded in and interacting with physical components (Smart System 2012). This definition regards CPS as an integration of both software and hardware, where the physical and virtual components can interact with each other through embedded instruments.

- **Cyber-Physical Systems** are physical and engineered systems whose operations are monitored, coordinated, controlled and integrated by a computing and communication core (Rajkumar et al. 2010). From this perspective, the focus of CPS is more about the control and communication of the physical system through the computing system. It highlights the function of remote control and monitoring of the real world by CPS.

- **Cyber-Physical Systems** are integrations of computation with physical processes, wherein networked embedded computers monitor and/or control physical processes based upon local (i.e. in-network) and remote (i.e. back-end) computational models (Krogh et al. 2008). Based on this definition, it can be concluded that CPS enables the computing system to control the physical system through a network.

- **Cyber-Physical Systems** are large-scale interconnected systems of heterogeneous components that are envisioned to provide integration of computation with physical processes (Lee 2007). Therefore, CPS provide a solution to integrate several heterogeneous components, so that the physical world can be well controlled by the computing system with different functions based on the users' purpose.

In general, CPS are used as an interaction system where the physical world and virtual world can communicate and interact with each other seamlessly. Considering for the purposes of this paper, a CPS is simply considered as the effective bidirectional integration of computation with physical processes. Embedded computers and networks monitor and control the physical processes with feedback loops, where physical processes affect computations and vice versa (Derler et al. 2012).

Key features of CPS
By definition identified above, a CPS involves a high degree of integration between computing (virtual) and physical systems (Greenwood et al. 2015). Distributed applications are also common which involve distributed management and/or distributed operations such as a power grid. Another feature of CPS is the ability to provide timely service in the face of real-time constraints (Wan and Alagar 2012).

In general, the key features of CPS can be summarized as integration, distributed system, real-time system, virtualization, adaptability, automation, heterogeneity, and uncertainty (Table 1). By integration, the CPS combines the physical and computing system through mutual information exchange and control, instead of only tracking the physical world with a computing system or vice versa (Wu and Li 2011). Besides, CPS provides distributed management for it can be a large system consisting of several distributed systems. In this way, by using CPS, multiple parties can remotely obtain access to the project from different places for project management or cooperation. Meanwhile, CPS is capable of real-time communication, which enables continuous integration and up-to-date information exchange between the virtual and physical systems. The integration between virtual and physical systems can be updated in real time. In terms of virtualization, CPS creates a virtualized interface for users to remotely analyze and track the physical system. It also enables all the physical components to be identified and recognized.
accurately in the virtual model (Penna et al. 2010). The feature of adaptability means that CPS is capable of adapting to changing situations through dynamic reorganizing /reconfiguration (Khaitan and McCalley, 2014). The automation feature enables the automatic control of physical system according to continuous tracking. During the automatic control process, actuators are triggered based on system analysis and command. From the perspective of heterogeneity, CPS integrate several different systems together with standard communication and information exchange. It also integrates various devices, including sensors, mobile devices, high-end workstations and servers (Wan et al. 2011).

Overall, CPS integrates the physical structure and its corresponding cyber systems seamlessly at all scales and levels. Automatic and resilient human-machine interaction is supported by CPS for improved control, efficiency and reliability of the physical systems (Lee et al. 2015).

Table 1: Key Features of CPS

<table>
<thead>
<tr>
<th>Researcher</th>
<th>Integration</th>
<th>Distributed</th>
<th>Real-time</th>
<th>Virtual</th>
<th>Adaptability</th>
<th>Automation</th>
<th>Heterogeneity</th>
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<tbody>
<tr>
<td>Wu and Li (2011)</td>
<td>Combination; networked</td>
<td></td>
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<td>Shi et al. (2011)</td>
<td>Integrated networked</td>
<td></td>
<td></td>
<td></td>
<td>adaptive</td>
<td>highly automation</td>
<td>complex</td>
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<tr>
<td>Anumba et al. (2010)</td>
<td>interaction</td>
<td>tagging and tracking physics</td>
<td>cyber capability in physic world</td>
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<tr>
<td>Wan and Alagar (2012)</td>
<td>sharing resource</td>
<td>distributed system: Geographically distributed</td>
<td>real-time</td>
<td></td>
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<td></td>
<td>heterogeneity</td>
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<td>Wan et al. (2011)</td>
<td>couple with physics</td>
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<td>heterogeneity</td>
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<tr>
<td>Geisberger et al. (2011)</td>
<td>networked;</td>
<td>distributed control; systems of system</td>
<td>adaptive</td>
<td>partial autonomy; human-machine cooperation</td>
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CPS APPLICATIONS

In exploring CPS applicability in temporary structures, it is important to understand its applications in other industry sectors where CPS has been adopted and developed for advanced management. In addition, a review of current CPS applications in the realm of the built environment could help to identify the current research gaps, examine CPS applicability, as well as to identify potential application areas in temporary structures monitoring.

CPS applications in other industries

CPS was initially developed in other industries such as manufacturing industry, power grid, transportation industry, and healthcare industry. Some of the applications in these industry sectors are briefly reviewed in this section.

Manufacturing industry
Smart manufacturing refers to the manufacturing industry which, with the application of CPS for the tracking and monitoring of a product throughout its life cycle, can optimize its performance and efficiency (Coalition 2011). Current manufacturing resource aggregation (MRA) cannot adapt to dynamic factors, which greatly impact the quality and efficiency of the manufacturing industry. In viewing this problem, Liu and Su (2011) pointed out that CPS can provide real-time information on physical resources and thus support the realization of dynamic MRA. Liu and Su’s study gives a new solution for dynamic MRA with the aid of CPS. Taking advantage of the real-time feature of CPS, Kaihara and Yao (2012) developed a Real-Virtual Integrated Scheduling System based on the concept that CPS is the combination of the computational and physical worlds (Lee 2007). Their developed system helps to manage dynamic changes at production sites through the dynamic scheduling of the real system and simulation of the virtual system.

The main challenges for CPS the implementation in manufacturing industry include network integration, affordability, and the interoperability of engineering systems (Aderson 2011). The use of CPS in manufacturing industry requires seamless connection between each node. While the manufacturing industry’s network has enabled the life-cycle management of products, the implementation of CPS requires high-speed, stable, and seamless communication for real-time inspection and control. Therefore, more integrated network should be set up before CPS can be fully implemented in this area. Due to the high cost of both retrofitting existing control system and the initial set up of CPS, there is no motivation for small and medium-sized companies to investigate CPS. Besides, most of the manufacturers use different kinds of engineering systems for production management, and even customize their own software and system. The lack of an information exchange standard regulating the data type of the manufacturing files from various manufacturers prohibits the quick promotion of CPS, for CPS has to be adjusted and re-designed for each manufacturing company due to the lack of interoperability of engineering systems (Smart Systems 2012).

**Power grid**

The smart grid is a complex ecosystem of heterogeneous (cooperating) entities that interact to provide the envisioned functionality (Karnouskos 2011). In view of the fact that the infrastructure for both the electric grid and water distribution systems is aging with technical and reliability problems, Krogh et al. (2008) proposed that the electric grid and other utilities can use CPS technologies for a smarter and more efficient system. CPS is valued as an integral part of smart grid (Karnouskos 2011). To verify the correctness of cyber-physical composition, Sun et al. (2007) introduced a model to avoid interference among components of a system. Furthermore, since CPS imposes increasing uncertainties on controlled systems, Zhu and Basa (2011) proposed a holistic theoretical framework and applied it to power systems. This framework helps to maintain an appropriate level of CPS operation even during unexpected system interruptions.

With CPS implementations in smart power grids, challenges to be dealt with include system security, data analysis, and the integration of new technologies. The system security requires that the system should not easily crash even when there is a high consumption demand, or when the system is attacked. Besides, while the use of CPS enables multiparty access to the power grid management system to get or provide energy to the system, such distributed accesses to the smart power grid impose the risk of hacker attacks. Because the power grid produces large amounts of data for analysis, an appropriate data fusion method is critical to CPS for automatic control of the power grid system. Besides, the integration of CPS with current power grid management system calls for great efforts in analyzing existing system, a proper way of adding CPS to existing power grid management system, as well as the use of new technologies for enhanced functions with use of CPS, such as energy storage technologies (Baheti and Gill 2011).

**Transportation industry**
Recent traffic problems, such as traffic jams and accidents, call for the improvement of transportation system (Ge et al. 2004; Gong and Li 2013). CPS offers the potential to an intelligent traffic system through real time detection of system status, optimal route plan, and adjustment of control strategies (Gong and Li 2013); and is valued as the promising approach to aerospace education, research, training, and accelerated workforce development (Noor 2011), and the transformation of the national airspace system (NITRD 2012). Four research areas, including (1) new functionality, such as higher capacity, greater safety, more efficiency; (2) integrated flight deck system for (semi)autonomous system; (3) vehicle health monitoring and management; (4) safety security of aircraft control system, have been identified for CPS applications to the future air transportation system (Baheti and Gill 2011). Mertins et al. (2012) also proposed a CPS application to aircraft maintenance repair and overhaul, with the aim to simplify and shorten the execution of Maintenance, Repair and Overhaul (MRO)-Processes which impact aircraft availability. To facilitate the application of CPS in the transportation domain, a low-priced intelligent vehicle with wireless sensor networks navigation, was designed (Wan et al. 2011). Furthermore, based on CPS theory, Gong and Li (2013) proposed a fusion framework for urban traffic control system, which aims to avoid traffic congestion and improve traffic efficiency. This study provides a theoretical foundation for CPS implementation in intelligent traffic system.

Safety and security, which are most important to the transportation industry, remain big challenges before CPS can be fully adopted (Smart System 2012). The safety threat means that the use of CPS may distract the attention of drivers and result in a higher risk of accidents. Besides, the safety of transportation systems is also highly impacted by system security when there are system logic problems of unmanned vehicles, system interruptions, and hacker attacks (NITRD 2012). All of these concerns call for a high confident CPS to be used for transportation management (Lintelman et al. 2008).

**Healthcare industry**

Healthcare increasingly relies on networked medical systems to take care of patients with special circumstances. An example is the use of sensors to track the conditions of patients during operations. However, these techniques should be assembled into a new system configuration, such as CPS, to match specific patient or procedural needs (Baheti and Gill 2011). It is envisioned that the next generation of healthcare systems would be secure and reliable systems with wired and wireless networked medical devices (Arney et al. 2010) and medical information systems (Sha et al. 2009). The application of CPS in healthcare involves the national health information network, electronic patient record initiative, home care, operating room, etc. (Shi et al. 2011). Lee and Sokolsky (2010) discussed current trends and promising research directions in the development and use of high-confidence medical CPS. To cope with the safety issues, Cheng (2008) proposed a method to allow the safe cyber-physical operation of a medical ventilator, a life-critical reactive device, to move breathable air into and out of the lungs of a patient with respiratory difficulties. This study also examined potential research areas so that the safety operation of CPS application in healthcare industry can be improved.

Several challenges for CPS application in healthcare industry remain to be tackled. For example, the complex relationship between a patient’s health condition and the required medical condition calls for an accurate algorithm with several parameters other than the time (Cheng 2008). In viewing the trend of medical CPS, Lee and Sokolsky (2010) identified the challenges raised by CPS, including safety of patients, collaboration and interoperability between several treatment systems to one patient at the same time, a simple patient model covering all needed information and a comprehensive simulation for test and validation, adaptive patient-specific algorithms with special concerns to unique parameters to a certain patient, and open interconnectivity standards for medical CPS.
CPS applications in the built environment

The construction industry is in need of continuous improvement in areas such as intelligent safety management, cost and resource management, scheduling, and energy conservation. With development in information technologies, recent research (discussed below) have recognized the potential benefits of CPS to the built environment from various perspectives, including: project delivery process, automatic construction site layout generation, construction progress monitoring, light fixture monitoring and control, and Structural Health Monitoring (SHM). Current CPS applications demonstrate how the built environment could benefit from CPS.

Project delivery process

Current project delivery processes are inefficient and there is a need of transformation so that greater control can be made through an integrated system. By identifying the limitations of previous efforts on managing the construction process, Anumba et al. (2010) demonstrated the need for CPS to improve the project delivery process, and proposed a CPS approach targeting the integration of virtual models and the physical world through a bi-directional flow of information. This provides reference for future research efforts in this research field.

Akanmu (2012) highlighted the mechanism and triggers for the bi-directional flow of information. Through use-case scenarios validation and expert interviews, CPS applicability was demonstrated in enhancing bi-directional coordination between virtual models and the physical construction world.

Automatic construction site layout generation

In view of the importance of resource layout and activities to the success of construction projects, Akanmu et al. (2015) proposed the use of CPS for construction site layout and developed an automated component level system for optimized and real time site layout. Case studies demonstrated that the developed system provides an effective means for real time construction site space tracking and the automatic generation of construction site layout.

Construction progress monitoring

Potential benefits of CPS to construction progress monitoring were highlighted by Olatunji and Akanmu (2015) with the development of an adaptive CPS approach for construction progress monitoring and control. Besides, Yang et al. (2015) proposed the use of vision-based method for construction performance monitoring, including the control of construction progress both at the project level (civil infrastructures and elements) and the operation level (construction equipment and workers).

Light fixture monitoring and control

Building on the previous studies, Akanmu presented an approach to improve light fixture monitoring through CPS integration between virtual models and physical light fixtures. A prototype system was developed and implemented for tracking, monitoring and controlling light fixtures throughout a facility life cycle (Akanmu et al. 2014). Other possible applications were also identified, such as management of urban infrastructure street lights, mechanical systems and other building components such as window blinds, etc.

Structural Health Monitoring (SHM)

SHM helps to prevent civil structural failure or costs by providing information and assisting in decision making for preventative measurements (Smart System 2012). To improve the evaluation of structural performance, recent research has applied CPS to SHM by integrating the computing elements and structural components. According to Hackmann et al. (2014), SHM represents an important application domain of CPS. To integrate damage detection and energy saving, they proposed a cyber-physical co-design approach to structural health monitoring using wireless sensor networks. This approach can selectively activate nodes in the damaged region so that
local damage is detected while allowing the rest of the nodes to remain asleep. Tidwell et al. (2009) pointed out the main challenges of CPS application to SHM, such as the actuator dynamics, complex interactions between physical components and their virtual models, and the computation and communication delays. To improve the hybrid real time testing, Tidwell et al. (2009) provided a highly configurable and reusable middleware framework for real-time hybrid testing. This study improves the high-fidelity real-time testing and promotes CPS applications in this area.

As shown in the previous sections, previous researchers have explored CPS applications and potential benefits in a variety of areas of the built environment. CPS has been identified as being applicable to various aspects of the construction industry by integrating and coordinating virtual and physical construction systems. However, CPS applications in the built environment are still limited to the project delivery process, construction site layout generation, construction progress monitoring, light fixture monitoring, and structural health monitoring of critical infrastructures. Few efforts have been made to take the benefits of CPS to temporary structures, whose performance may have great impacts on construction quality and workers' safety. Various applications of CPS enabling technologies (discussed in the following section) have been implemented for enhanced monitoring of temporary structures, which indicates CPS applicability and potential benefits to the temporary structures.

**CPS applicability in temporary structures monitoring**

The realization of a complete CPS relies on several supporting technologies to integrate the virtual model with the physical construction (Akanmu et al. 2014). Although there have been no CPS applications for the temporary structures monitoring, some of the supporting technologies of CPS, such as Building Information Modeling (BIM) and Data Acquisition system have been utilized for enhanced monitoring of temporary structures. A brief review of these CPS supporting technologies’ applications to temporary structure helps to identify their benefits and limitations, so as to provide a clear understanding of CPS applicability and potential benefits to temporary structure management.

**Use of BIM for temporary structures management**

For better virtualization of temporary structures, Chi et al. (2012) proposed to develop BIM objects of temporary structures, such as scaffolding system and formworks. These BIM objects will be embedded with design, construction and safety information as references to other parties. Similarly, a safety-rule based BIM for temporary structures (such as a scaffolding system), was developed, with special focus on automatically identifying and eliminating potential fall hazards during the design stage (Zhang et al. 2015). In addition to adding safety regulations to the BIM model of temporary structures, Kim et al. (2011) presented a safety identification system for temporary structures, which identifies and predicts potential safety hazard by simulating construction schedules and checking the location of temporary structures at each step. Besides, Li et al. (2008) proposed to integrate the design and construction of temporary structures through virtual prototyping. In view of the difficulties in identifying appropriate temporary structures to be shared among projects for cost saving, Kim et al. (2014) proposed the use of BIM technology for quick identification of sharing solutions of temporary structures among different projects. All of these efforts have benefited the visualization, design, and safety planning of temporary structures.

**Use of DAQ for temporary structures management**

A DAQ refers to computer based systems with digital input and output (UEI 2006). With developing technologies, DAQ has been recognized as important to prevent construction failures by providing information, and has been increasingly utilized for temporary structures
management (Moon et al. 2012). These efforts include the use of Radio Frequency Identification (RFID), wireless sensor networks, and videos. As early as 2007, Yabuki and Oyama (2007) used RFID to record the usage history of temporary structures, so that project managers can understand how long the temporary structures have been used, in order to decide whether it is safe to keep using them. Ubiquitous sensor network technology can be used to determine the structural performance of temporary structures by analyzing deflection, load, strains, etc. (Moon et al. 2012). It provides a real-time approach to monitor formwork operations as a means of preventing structural failures. Most recently, Jung (2014) proposed the use of video method to detect potential defects of temporary structures. This system will continuously record the images of temporary structures, predict potential structural defects, and send warnings if there are potential hazards. With the development of DAQ, more structural information of temporary structures can be obtained for comprehensive structural analysis.

While the supporting technologies of CPS in temporary structures are still at the early stages of implementation, their benefits and limitations highlight the opportunities for further applications of CPS. Implementation of CPS in preventing failures and promoting safe construction techniques of temporary structures remains promising as discussed below.

**POTENTIAL AREAS FOR CPS APPLICATIONS IN TEMPORARY STRUCTURES**

For the purpose of identifying potential areas for CPS application, temporary structures which have historically been involved in a high record of failures were selected for discussion. These cover two general categories - temporary performance stages and temporary support systems.

**Temporary performance stages**

A temporary performance stage is a structural assembly that is used for an outdoor performance for less than 90 days of one year (Wainscott 2011). Collapses of temporary performance stages have occurred frequently in recent years. In 2008, two of the stages for the Rocklahoma music festival collapsed, resulting in ten injuries when severe winds struck northeast Oklahoma. In 2009, the main stage of Big Valley Jamboree in Toronto collapsed, killing one and injuring at least seventy people during another wind storm. Additional collapses occurred in 2011, including the well-publicized Indiana State Fair Grandstand, resulting in multiple fatalities and over fifty people injured in total. More recently, the Downsview Park in Toronto collapsed in 2012, killing one person and injuring three others, while another stage roof collapsed in North Carolina in 2013 during bad weather (Kleinosky 2012). These accidents are also related to the lack of authoritative standards for temporary structures and performance stages (McKinley 2011). This makes the need for a proactive monitoring system more urgent (Yuan et al. 2014).

**Temporary support systems**

Temporary support systems serve to help carry or support a structure or provide safety access for workers during the construction process. They are categorized into four types (discussed below): scaffolding systems, earthworks, formwork, and temporary bracing systems.

Scaffolding is used to provide temporary safe working platforms for the erection, maintenance, construction, repair, access or inspection of structures or other building systems (Grant and Pallett 2012). According to the U. S. Bureau of Labor Statistics, approximately eight workers working on scaffolding system are hurt each month at the United States construction jobsite (BLS 2013).

Sheeting and shoring (using systems such as steel soldier piles, sheet piles, and slurry walls) are used to prevent soil movement and cave-ins during earth excavations. Inappropriate design and installation of earthwork shoring and sheeting systems results in numerous accidents each year, making earthworks a substantial risk for workers.

Formwork systems are primarily used for standard poured-in-place concrete construction. Formwork construction is associated with a relatively high frequency of disabling injuries and
illness (Hallowell and Gambatese 2009). This is now recognized as a serious problem (Shapira 1999).

Temporary bracing systems are used to keep a structure or building system stable before the permanent bracing is installed or the element becomes self-supporting. Insufficient bracing is cited as one of the four top causes of failures in steel structures under construction (Kaminetzky 1991). The structural load is usually analyzed by conceiving the whole structure as a completed entity, and there is frequently a lack of design or proper implementation of the temporary bracing systems. Often, the specific provisions and requirements of temporary bracing systems are left to the workers on the job site that may not have the qualifications or expertise for proper execution (Feld and Carper 1996).

Application scenario

Scaffolding system, listed below, has been selected for the analysis of CPS application in temporary structures monitoring for two reasons. First of all, scaffolding systems, ranking third among top 10 OSHA violations in the year of 2013, accounts for a large amount of fatalities and injuries in construction industry (U.S. Department of Labor 2014); second, the principles of structural monitoring of scaffolding system are similar to the ones of other types of temporary structures, which indicates that the TSM of scaffolding system can be easily adopted by other temporary structures.

Workers and equipment on scaffolds have the capability to impose movement or inclination that exceeds design limits, which in turn can result in collapse. Unfortunately, it is often left to workers to determine if the scaffolding is overloaded, shifting or otherwise not performing as intended (Feld and Carper 1997). In such cases, CPS can be used to monitor the movement and load conditions imposed by the placement of materials and the movement of workers on the scaffolds. For example, a sensor can be attached to the scaffolding to continuously detect its loading information, and send dynamic response data to a virtual model. Based on structural analysis and performance parameters, the virtual model can be updated with the live condition, predict the stability of the scaffolding and, when appropriate, issue an instruction to the actuator on the job site or to site personnel to take appropriate precautionary measures. For example, hydraulic cylinders can be place at the side of scaffold posts as actuators. Upon identification of early signal of inclination, these actuators act to hold the inclined posts according to system commands. In addition to the remote control of actuators, the project manager or structural designer can also send instructions from the virtual model to the physical component on the job site to guide workers’ activities. An application scenario for structural monitoring of scaffolding using CPS is illustrated in Figure 1.
As identified in Figure 1, a CPS can be developed for structural monitoring of scaffolding systems by enabling bi-directional communication between the Physical scaffold components and their virtual models. To be specific, first of all, the DAQ placed on scaffold components on the job site collect structural data (such as information of inclination, loading, deflection, etc.) and send all data to the database; Second, the structural information is continuously inquired by the virtual models for structural performance analysis; Third, the virtual models are updated based on the most recent structural analysis. Once there is potential hazard, the components in question will be marked in red color for attention; Fourth, once received the warning, project managers and competent person analyze the structure performance of scaffolding system in virtual model and send instructions through virtual models to the DAQ or other portable devices; Finally, workers act to correct the situation based on the instructions.

POTENTIAL BENEFITS AND BARRIERS

Based on the section of “key features of CPS” and “applicability of CPS in temporary structures” discussed above, several potential benefits and barriers to CPS implementation are identified as follows.

Potential benefits

CPS offers the potential for improved monitoring of temporary structures through real time coordination between virtual and physical systems. By systematically implementing CPS, a number of potential benefits can be achieved as follows:

- **Real time inspection**: in lieu of inspecting specific influential factors, CPS can monitor the performance of temporary structural components in real time, and provide warnings that can help to ensure structural stability.

- **Tight coordination between physical component and virtual model**: CPS enables bi-directional communication between physical components and their virtual representations. Through the “Physical-to-cyber Bridge”, the movement of physical
components will be detected by sensors and sent to the virtual model, where the difference between designed and actual structure will be highlighted on the model. Through the “Cyber-to-physical Bridge”, once potential hazards are detected, safety alerts or instructions can be sent from the virtual model to the workers or a mechanism to automatically stabilize temporary structures can be actuated if appropriate.

- **Remote and multi-party access for management**: due to the bi-directional information loop between the physical and virtual components, the structural performance can be remotely monitored using virtual models. CPS enables multiple parties to obtain access to the structural monitoring system from different locations through the interface of virtual models. This function benefits project managers, structural designers, owners and other involved parties for routine monitoring, potential structural problem analysis, instruction to avoid potential dangers, and enhanced collaboration.

- **Early warning with customized safety level**: Implementation of a dynamic CPS environment has the potential to shorten the time interval between the on-set of an initial hazard and potential collapse. In addition to the quick identification of potential problems, the system can prevent hazardous situations by setting a safety factor for the performance of temporary structures. In this way, instead of having alarms when there are already structural failures, an early warning will be sent once there is a trend or high possibility of potential structural failures. The safety factor can be used as recommended or customized if the user wishes to have a higher level of safety.

- **Knowledge base to predict potential hazards**: during the structural monitoring of temporary structures, all the performance data of the temporary structures and instructions at different situations is recorded in database. The relationship between instructions and structural problems can be learned and identified, which enables CPS to automatically provide suggestions for instructions when having similar structural problems.

**Potential barriers to CPS implementation**

The preceding discussion has demonstrated that there are several temporary structures applications that can benefit from the implementation of CPS for monitoring and performance purposes. However, there are also barriers and technical issues to be addressed. Some of these include:

- **Security**: There is growing concern about cyber-attacks on CPS, as computing systems and sensor networks are unable to work effectively under malicious attacks. Furthermore, attacks on CPS used in commercial business or hospital environment might disclose personal information (Cardenas et al. 2008).

- **Reliability**: Random failures in CPS may occur due to system errors, inaccuracy of data, and data interference. Sensed data is susceptible to a reduction in accuracy due to interference from other signals such as Wi-Fi or other electronic devices (Akanmu 2012). However, modern construction job sites involve numerous kinds of electronic equipment which impacts the accuracy of sensed signals. Physical damage to a sensor due to construction operations or impact is also a possibility.

- **Training of workers**: CPS involves the management and installation of new technologies, including hardware such as sensors and actuators on job sites. These technologies need to be implemented, tested and inspected on a continuous basis. It requires that construction personnel are adequately trained in the use of these new technologies.
• **Financial issues:** although the price of sensors has dropped, accurate and quick detection requires a large number of sensors to work simultaneously. In addition, the use of actuators, the connection system between sensors, information platform and actuators, and the training of workers have cost implications that will need to be addressed.

**SYSTEM REQUIREMENTS AND ARCHITECTURE**

In order to use CPS for enhanced temporary structures monitoring, one should identify the system requirements, so that the expected benefits of CPS in temporary structure can be achieved. Based on the identified system requirements, a system architecture is presented as an example of how CPS works in temporary structures monitoring.

**System requirements**

A summary of system requirements is presented below under appropriated headings:

**Visualization**

The requirements of visualization include two aspects – visualization of temporary structures in question and the visualization of instructions. The virtual model of temporary structures is one of the basic parts of CPS, which provides user interfaces for remote inspection and control of the physical model. The virtual model should be consisted of digital components which unique ID, so that can be recognized and inspected independently by computing system. It is recommended that the virtual model provides basic properties and information of temporary components, which assists project managers in structural analysis and decision making in preventing potential collapse. Besides, the instructions entered in the virtual model will be sent to the DAQ or portable devices. To avoid misunderstanding, the instructions, along with the picture identifying the components in question should be presented clearly to workers.

**Real-time and Remote Communication**

To enable real time and remote interaction between the temporary structures and their virtual models, continuous wireless connection must be set up. Since the temporary structures work in a dynamic environment, the monitoring of the updated structural status of a temporary structure should be in real-time, so that potential structural defects can be quickly identified and an early warning issued before accidents occur. An example of such a network is Socket, which is an endpoint for communication between two machines. Database can be used both for data storage and real time data communication between virtual model and the physical components.

**Adaptability between Virtual and Physical World**

Adaptability is a big concern when identifying the hardware and software for CPS implementation. To enable customized function at the interface of the virtual model, the software used for virtual model development should provide an Application Programming Interface (API). Similarly, the software used for data acquisition or control devices, should also provide an API so that a control activity can be initialized on the control devices when needed. Besides, the data format should be well examined to make sure that the information exchange at the database platform between DAQ and the virtual model works well.

**Data Precision and Resolution**

The structural analysis of temporary structures has a high requirement for the data accuracy and resolution, because of the potential for failures due to the dynamic construction environment. The data accuracy should be as high as 95% for an accurate and confident level of structural analysis. Besides, the selection of the resolution of the DAQ is based on the level of details of temporary structures performance to be checked. It is recommended to use the one with
appropriate level of precision due to concern of noise interference (Moon et al. 2012), so that more detailed structural performance of temporary structures can be captured.

**System Security**

Two concerns should be addressed for system security: continuous information exchange between temporary structures and virtual models, and the accuracy of system logic for correct system response. Real-time structural monitoring is based on a continuous information exchange loop. If there was an interruption or noise that disrupts the connection of the information exchange, the real-time monitoring of temporary structures would fail. Therefore, a back-up connection should be designed to keep the system working well even when the primary connection between temporary structures and virtual models is broken. The second concern is to make sure that the system will respond as designed under different circumstances. Take the hydraulic cylinder for example, as we discussed before, the hydraulic cylinder placed by the side of scaffolding posts can be used to hold the inclined post so as to prevent potential collapse. However, if the cylinder didn't work due to system error, the collapse would never be prevented. In general, the system logic should be well tested for security consideration.

**System Architecture**

The CPS for temporary structures monitoring consists of physical temporary structures and their virtual models, which are integrated through a CPS bridge. According to the system requirements identified in the previous section, the system architecture is demonstrated in Figure 2. The CPS bridge provides bi-directional communication between physical and cyber system through the use of communication networks and databases. To enable the information access to physical temporary structures by the cyber system, a DAQ is attached to the physical structures; for human-machine interaction and remote inspection of the physical structures, a BIM plug-in is developed at the end of virtual model; besides, the portable devices are used as communication tools between cyber system and safety professionals whose corrective action to the physical structures are made based on the instructions from cyber systems.
While the use of CPS has been highlighted as a promising solution to temporary structures, a few limitations should be pointed out for further exploration. First of all, there is a lack of guidance to the selection of DAQ technology for different application scenarios. Based on the objective and characteristics of objects to be monitored, different DAQ approaches (such as image-based approach and embedded sensors) should be used for to support the development of CPS; Finally, the difference between the construction industry and other industry sectors requires careful design of control methods from the virtual model to the physical structures. Due to the dynamic working environment on the construction jobsite, an unexpected change or control of the performance of temporary structures may put the construction workers nearby in danger. This can be taken care of by taking into consideration the space and working relationship between the construction workers and the temporary structures.

**CONCLUSION**

Based on the preliminary literature review, a CPS was proposed as a potential solution for monitoring the stability of temporary structures. The current problems of temporary structures and key features of CPS have been summarized to establish the need for CPS in temporary structures monitoring. A typical type of temporary structures, scaffolding system, is analyzed for CPS applicability. However, due to the similar principles of monitoring most of the temporary structures, CPS application can be expanded to other types of temporary structures as well. Besides, the potential benefits and barriers to CPS implementation in temporary structures have also been identified. For better understanding, a system architecture with system requirements is proposed as an example of how CPS could be implemented for temporary structure monitoring.

A number of key conclusions can be drawn from this study. Generally, the temporary structures failure remains a big risk to the safety management of construction projects. The
inadequate monitoring of temporary structures calls for a more proactive, intelligent monitoring system, such as CPS. CPS provides an effective way of integrating the real world with its virtual representation, and has been implemented in several industry sectors, such as the manufacturing industry, power grids, the transportation industry, and the healthcare industry. More recently, CPS has shown potential benefits to the built environment through its successful application in structural health monitoring and facility management. Therefore, CPS offers an opportunity to address the current problems and safety issues associated with temporary structures, including temporary performance stages and scaffolding. To be specific, a CPS for temporary structures monitoring enables remote control, “on physical component instructions”, and real-time interaction between temporary structures and their virtual representations. Finally, a CPS for temporary structures monitoring can be developed based on the system requirements and system architecture presented in this paper.

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REFERENCES


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