The Use of Cyber-Physical Systems in Temporary Structures – An Exploratory Study

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ABSTRACT

The construction industry has had a high record of structural failures and safety problems for decades. Some of these relate to the inadequacy or instability of temporary structures. In many cases, these structures are regarded as static structures without appropriate monitoring of temporal changes in their stability. Developments in information and communications technologies, notably the advent of Cyber-Physical Systems (CPS), are changing the way in which structures are monitored. While significant deployments are being made in the structural health monitoring of constructed facilities, such as bridges, dams and other civil infrastructure, inadequate attention has been paid to temporary structures. With the bidirectional coordination possible between physical artefacts and their virtual representations, CPS offer an approach that can facilitate the monitoring and active control of temporary structures in such a way as to prevent structural failures and safety hazards on the job site. This paper reviews the key features of CPS, examines current CPS applications in the built environment and analyzes the applicability, potential benefits and barriers for CPS application to temporary structures. It identifies the promising application areas, and discusses how CPS could be applied in these contexts and the potential benefits.

INTRODUCTION

In the general sense, a Cyber-Physical System (CPS) is defined as the 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). CPS have been promoted and applied in a number of areas including manufacturing, power grids, transportation, and healthcare (Shi et al. 2011).

The construction industry is developing applications in order to take advantage of CPS. Akanmu (2012) investigated the applicability of CPS in the built environment, and developed two prototype systems for CPS application, including light fixture management and physical building integration. Other researchers are trying to implement CPS for real-time Structural Health Monitoring, SHM (Tidwell et al. 2009). However, while significant deployments are being made in the SHM of constructed facilities, the design and construction of temporary structures (i.e. scaffolding, temporary support systems including bracing, sheeting and shoring, formwork, and underpinning of foundations) has received little attention (Fabiano et al. 2008). In many cases, temporary structures are regarded as static structures that do not need monitoring, yet such dismissal can lead to failures and severe accidents. With the bi-directional coordination possible between physical artefacts and their virtual representations, CPS offer an approach that has the potential to facilitate the monitoring and active control of temporary structures in such a way as to prevent structural failures and safety hazards on the job site.

KEY FEATURES OF CYBER-PHYSICAL SYSTEMS (CPS)

By definition, a CPS involves a high degree of integration between computing (virtual) and physical systems (Wu and Li 2011), which is supported by the networked implementation of CPS (Anumba et al. 2010). 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).

Overall, CPS require a high degree of automation but at the same time can provide automation benefits. Man-machine interaction is well supported in CPS, and the application of advanced feedback control technologies has been widely applied to these systems (Shi et al. 2011).

CURRENT CPS APPLICATIONS

Applications in other industries

CPS were initially developed in other industries before its benefits were recognized by the construction industry. In the manufacturing industry, CPS have been deployed to help manage dynamic changes in production (Kaihara and Yao 2012). Relative to the power grid, smart grid technology is being developed using CPS applications (Krogh et al. 2008). CPS have also been implemented in the transportation industry to promote the development of intelligent traffic systems (Gong and Li 2013). The healthcare industry is increasingly relying on CPS for networked medical systems and health information networks (Shi et al. 2011).

Applications in the built environment

A number of current CPS applications represent an overview of how the construction industry would benefit from CPS, as well as to formulate potential uses of CPS in this domain:

- <u>Project delivery process:</u> Anumba demonstrated the need of CPS for an efficient project delivery process based on an approach in which virtual models and the physical world can be integrated through bi-directional flow of information (Anumba et al. 2010).
- <u>Light fixture monitoring and control:</u> 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. 2012).

- Structural Health Monitoring (SHM): SHM helps to prevent structural failures and cyber-physical systems have been deployed for real-time structural health monitoring of civil structures, such as bridges, cantilever beams and trusses (Lynch el al. 2009, Hackmann et al. 2010).

As is shown in the previous section, previous researchers have investigated CPS applications and potential benefits in a variety of areas. CPS have been identified to be applicable as a future tool in the construction industry that integrates and coordinates the virtual and physical systems.

More recently, researchers have recognized the benefits of modeling technology for the safety management of temporary structures (Chi et al. 2012, Kim and Ahn 2011), and are using sensing technology to monitor formwork operations as a means of preventing structural failures (Moon et al. 2012). This work is in the early stages of implementation and the opportunity for expanded applications of CPS in preventing failures and promoting safe construction techniques remains promising as discussed in the remainder of this paper.

CPS APPLICATION IN TEMPORARY STRUCTURES

Overview

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 & 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. 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. 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 (Feld and Carper 1997, Stewart 2010).

Recent developments in information and communication technologies, such as sensing and modeling technology in temporary structure management, notably CPS applications in improved structural health monitoring, provides the potential of temporary structure monitoring. The use of CPS provides 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 sensors 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 causations.

Potential application areas

For the purpose of this review, temporary structures which have historically been involved in higher numbers of failures were chosen for discussion. On that basis, the temporary structures included in the discussion below involve the two general categories of temporary performance stages and temporary support systems.

Temporary performance stages: A temporary performance stage is defined as 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. These accidents are also related to the lack of detailed standards for temporary structures and performance stages. This makes the need for a proactive monitoring system (such as CPS) more urgent.

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 five types for the purpose of this discussion:

- Scaffolding systems: Scaffolding is used to provide temporary safe working platforms for the erection, maintenance, construction, repair, access or inspection, etc. of structures or other building systems. (Grant and Pallett 2012). According to the U. S. Bureau of Labor Statistics, approximately eight workers are hurt every month in scaffolding collapses throughout the U. S.
- Earthworks: Sheeting & shoring using systems such as steel soldier piles, sheet piles, and slurry walls, are used to prevent soil movement and cave-ins during the excavation of earth. Inappropriate design and installation of earthwork shoring & sheeting systems results in numerous accidents each year, making earthworks a substantial risk for workers.
- Formwork: 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), and its related safety issue has become a serious problem (Shapira 1999).
- Temporary Bracing Systems: 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).

Applicability analysis

Two types of temporary structures, listed below, have been selected for this conceptual analysis of the applicability of CPS in temporary construction.

1) Temporary performance stages: Three major causes of failure or collapse involving temporary performance stages include the lack of engineering review after the stage was erected, and the difference between the actual installations compared to the engineering design requirements (Thorn 2012). Instead of requiring extra efforts from engineers, CPS work in conjunction with current designs. By developing a virtual model of a temporary performance stage, CPS offer the ability to automatically compare the performance parameters of the built construction to the actual construction. For example, CPS offer the potential to check the built assembly against a virtual model to compare stiffness, stability and load capacity.

In a wind storm, CPS offer the ability to perform real-time analysis of wind and other temporal and variable load conditions by examining the information from sensors attached to the structural components, such as roof membranes, guy lines and structural connections. This analysis compares actual loads and the capacities of structures, which can then be reviewed for potential collapse conditions and provides early warning to prevent catastrophes.

2) Scaffolding: Workers and equipment on scaffolds have the possibility of imposing 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. In such cases, CPS can be used to monitor the movement and load conditions imposed by the placement of materials and even the movement of workers on the scaffolds. For example, a sensor can be attached to the scaffolds to continuously detect its position in three dimensions, and send dynamic response data to a virtual model. Based on structural analysis and performance parameters, the virtual model can simulate 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. Such as procedure works for all aspects of the scaffolding from overloaded support members to problems related to bearing on unstable ground.

Potential benefits

Overall, the application of CPS to temporary construction elements provides an approach for better 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 noted below:

- Real time inspection: in lieu of inspecting specific influential factors, CPS examine the performance of temporary structure components every few seconds, and takes into consideration all loads imposed on the components, thus ensuring structural stability.

- Quick problem identification: Implementation of a dynamic CPS environment has the potential to shorten the time interval between the onset of an initial hazard.
- Automated sensing and control: CPS enable bi-directional communication between physical components and their virtual representations. From the job site to the virtual model, 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. From the virtual model to the job site, once potential hazards are detected, safety alert will be sent from the virtual model to the workers or automatically stabilize temporary structures.

Potential barriers to implementation

The preceding discussion has demonstrated that there are a number of temporary structural applications that can benefit from the implementation of CPS for monitoring and performance purposes. However, there are several barriers and technical issues to address and be aware of in the implementation of CPS in temporary construction. Some of these include:

- Security: There is a growing concern about cyber-attacks on CPS, as computing systems and sensor networks are unable to work 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 and background electronic noise. Physical damage of a sensor due to construction operations or impact is also a possibility.
- Training of workers: CPS involve the management and installation of new technologies, including hardware such as sensors and actuators on job sites. This technology needs to be installed, 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.

CONCLUSIONS AND FURTHER WORK

This paper has discussed the potential of using CPS in temporary structures. Two specific areas, temporary performance stages and scaffolding systems, were examined relative to the implementation of CPS. In addition, the potential benefits and barriers associated with CPS applications in temporary structures have been identified. It can be concluded from this exploratory study that:

- A CPS is an effective way to integrate physical artifacts and their virtual representations;

- The application of CPS is growing in many other industries including manufacturing, power grids, transportation, and the healthcare industry;
- There is considerable potential for CPS applications in the construction industry. Initial success has been in structural health monitoring and building energy performance monitoring /control, but there are numerous other potential application areas;
- CPS offer an opportunity to address the current problems and safety issues associated with temporary structures. In particular, CPS applications have potential in the design and operation of temporary performance stages and scaffolding systems, and can help to improve safety and avoid structural failures.

Further work in this study will focus on the development of a CPS for scaffolding system monitoring. This will involve system requirement analysis, the modeling of physical components, system development, laboratory experiments, and performance evaluation.

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