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Cyber-physical systems for temporary structure monitoring

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ABSTRACT

Information technology-based methods, such as Cyber-Physical Systems (CPS), play an important role in industrial transformation and evolution. However, while significant efforts have been made towards CPS application in several other industry sectors, the exploration of CPS benefits and applicability to the construction industry is at the initial stage. While CPS has been identified as a promising solution to address problems in the construction industry, few explorations have been made on CPS application to temporary structures, which have significant safety issues that urgently need to be addressed. With a focus on the enhanced monitoring of temporary structures to prevent potential structural failures, this study proposed a CPS-based temporary structures monitoring (TSM) system that integrates the virtual model of a temporary structure and the physical structure on the construction jobsite. In doing this, the applicability of CPS to temporary structures monitoring is investigated, and end user requirements and system requirements are identified for system design. In addition, a system architecture and a description of the issues surrounding the choice of a system development environment are presented. For better understanding of how the TSM works, aspects of the developed CPS-based TSM are presented with system workflow and simulated examples of the structural monitoring of a scaffolding system. The potential benefits and barriers to CPS implementation in temporary structures, along with future research based on this study, are highlighted.

1. Introduction

Cyber-Physical Systems, commonly known as CPS, can be termed as the effective bidirectional integration of computational resources with physical processes. Embedded computers and networks monitor and control the physical processes with feedback loops, where physical processes affect computations and vice versa [1]. By definition, a CPS involves a high degree of integration between computing (virtual) and physical systems [2], which is supported by the networked implementation of CPS [3]. Distributed applications are also common which involve distributed management and/or distributed operations such as a power grid. Other features of CPS include the ability to provide timely service in the face of real-time constraints [4], to adapt to changing situations through dynamic reorganizing/reconfiguration [5], to automatically control a physical system based on continuous tracking [6], and to integrate several different communication systems and devices [6].

As indicated by the key features, CPS offers a potential solution to addressing emerging problems, and has been implemented in several industry sectors. In the manufacturing industry, CPS has been deployed to help manage dynamic changes in production [7]. Relative to the power grid, smart grid technology is being developed using CPS applications [8]. CPS has also been implemented in the transportation industry to promote the development of intelligent traffic systems [9]. The healthcare industry is increasingly relying on CPS for networked medical systems and health information networks [5]. These initial attempts of CPS applications in the industry sectors mentioned above have given rise to the recognition of importance of CPS to the construction industry. As a result, CPS applicability and potential benefits have been explored in various areas of the construction industry, including project delivery process [3], light fixture control and monitoring [10], structural health monitoring [11], and temporary structures monitoring [12]. Based on these investigations, CPS has been identified as having considerable potential in the construction industry, particularly in addressing those problems that require bidirectional coordination between physical systems and their virtual representations.

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

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defined as the elements of civil engineering work, which support or enable the permanent works [13]. 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 [14].

In the construction industry, which accounts for more than one third (36%) of all U.S. workplace fatalities [15], the safety problem relative to temporary structures remains serious [14]. 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 (Baileys Crossroads, VA), killing 14 construction workers and injuring 34 others [16]. 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 [16]. A major scaffold system on a 49-story building on 43rd street in New Yorks 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 [17]. In general, it is estimated that three quarters of construction workers work on or near temporary structures [18]. The improper management of temporary structures results in 100 deaths, 4500 injuries, and costs $90 million every year [18]. Thus the improvement of temporary structures monitoring is urgently needed [14].

Recent advances in information technologies have resulted in the emergence of Cyber-Physical Systems (CPS), which offer a promising and more effective approach to temporary structures monitoring [12]. 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 in 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 presents the approach being adopted in the development of a CPS that is intended to improve the safety of temporary structures through real-time monitoring. It starts with a review of conventional approaches to temporary structures monitoring and existing CPS applications, and uses these to make the case for CPS deployment in temporary structures monitoring. Based on interviews with industry experts and professionals, end user requirements and system requirements are then analyzed to assist system design. This is followed by a presentation of the system architecture and system development environment (including the software and hardware requirements) for the CPS-based TSM. The key features of the prototype system are presented and its operation illustrated with a simulated frame scaffold example. In the concluding part of the paper, the potential benefits and limitations of the study are outlined and suggestions made on possible future research trajectories.

2. Necessity and applicability of CPS to temporary structures monitoring

In order to understand the need for CPS use in temporary structures monitoring, as well as to establish the feasibility of a CPS-based TSM, a comprehensive literature review was conducted with a focus on conventional IT-based methods of temporary structures monitoring, and CPS applications in the construction industry.

2.1. Conventional approaches to temporary structures monitoring

Given the seriousness of the safety problems of temporary structures, considerable efforts have been made to address these. Some of these include OSHA regulations, safety training programs, and industry safety practices. To be specific, OSHA has formulated safety requirements for the design, installation, maintenance, and dismantling of temporary structures. For example, during the lifecycle of temporary structures, a competent person and a qualified person are required for safety inspection and management of temporary structures. Besides, a variety of Personal Protection Equipment (PPE), such as lifelines and hardhats, is mandatory so as to prevent potential injuries to construction workers. In order to increase the safety awareness of construction workers, a number of safety training programs are also required and are made available by OSHA. The main purpose of the safety training program is to educate workers on the identification of potential hazards, and to promote safe working behaviors in accordance with OSHA regulations. In addition to these efforts made by OSHA, various industry safety practices with regard to temporary structures are provided by industrial organizations as references or guidance to the industry practitioners.

2.2. Related research on IT-based temporary structures monitoring

Apart from efforts on safety regulation and training programs, some studies have been conducted on improving temporary structures monitoring with the aid of IT-based methods. A summary of these studies is presented below and their limitations highlighted.

2.2.1. Use of building information modeling for temporary structures monitoring

For fast modeling of temporary structures, Chi et al. [19] proposed to develop BIM objects of temporary structures, such as scaffolding systems and formworks. These BIM objects come with two main benefits — modularized electronic temporary structure model available for designers to integrate into other BIM models and the capability to integrate temporary structure models with relative regulations, such as the safety requirements of each temporary structure. Similarly, a safety-rule based BIM for temporary structures (with a scaffolding system as an example), was developed, with special focus on automatically identifying and eliminating potential fall hazards during the design stage [15]. In addition to adding safety regulations to the BIM model of temporary structures, Kim et al. [20] presented a safety identification system for temporary structures, which identifies and predicts potential safety hazards by simulating construction schedules and checking the location of temporary structures at each step. Similarly, Kim and Fischer [21] pointed out the advances in BIM for the sharing plan of temporary structures to be used among different construction job sites by accessing construction activity conditions (such as construction speed, direction, pattern of action) and geological information from BIM models. Furthermore, Li et al. [22] proposed the use of virtual prototyping technology to assist in the decision of suitable construction method and preparation of construction schedule. This is further demonstrated through a case study of a 70-story office building, including the virtual prototyping of temporary structures. All of these efforts have contributed to improving the visualization, design, and safety planning of temporary structures.

2.2.2. Use of data acquisition (DAQ) systems for temporary structures management

A DAQ system refers to computer based systems with digital input and output [23]. With developing technologies, DAQ systems have been recognized as important to prevent construction failures by providing structural stability information, and have been increasingly utilized for temporary structures management [24]. These