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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 efforts include the use of RFID (Radio Frequency Identification), wireless sensor networks, and videos. As early as 2007, Yabuki and Oyama [25] have used RFID to record the lifetime 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. [24]. The ubiquitous sensor network provides a real-time approach to monitor formwork operations as a means of preventing structural failures. Most recently, Jung [26] proposed the use of a video-based method to detect potential defects in 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 systems, more structural information on temporary structures can be obtained for comprehensive structural analysis.

2.3. Limitations of conventional methods

Due to the implementation of OSHA regulations, safety training programs, and industry safety practices, the fatality rate of the construction industry has reduced significantly. However, a recent study [27] on safety records shows that there are still numerous safety problems that need to be addressed. Recent temporary structures failures reveal that there are still some temporary structures, such as indoor and outdoor theatrical stages, which are not covered by any safety regulations [28]. Furthermore, even with enough safety regulations and training programs, temporary structures failures could not be fully prevented as the workers tend to work under great pressure and make mistakes unconsciously [29]. Besides, as a passive method of protection, the use of PPE can only try to reduce the degree of injury to workers, instead of avoiding potential hazards. Other researchers [15,20] have explored the benefits of IT-based methods to prevent potential failures of temporary structures. However, most of the research focused on the safety design or plan of temporary structures with limited consideration of the dynamic environment on the construction jobsite. Besides, the proposed methods for real time inspection of temporary structures [24] are limited to passive inspection with few interactions between the inspection system and the physical temporary structures. Finally, the applications of CPS in the construction industry are still limited with very few explorations of CPS applications in temporary structures monitoring.

2.4. Applicability of CPS to temporary structures monitoring

While the IT-based methods [20,24,26] discussed earlier are still at the early stages of implementation in temporary structures, as part of the enabling technologies of CPS, 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 by Yuan et al. [12], the applicability of CPS can be validated from two perspectives. With regard to technology support, there have been various implementations of CPS enabling technologies such as virtual prototyping, DAQ, and communication networks [30]. Besides, the applications of CPS have been successfully explored in other industry sectors as discussed earlier in this paper, which demonstrated the availability of enabling technologies for CPS implementation in temporary structures monitoring. There have been several efforts that analyzed and identified CPS applications in the construction industry. Examples include the exploration of CPS benefits to project delivery progress [3], the application scenarios of CPS in potential areas of the construction industry, such as building components management [30] and temporary structures monitoring [12], lighting fixture monitoring based on CPS [31], and the use of CPS for structural health monitoring of critical infrastructures [11]. Many of these previous efforts have confirmed the applicability of CPS to temporary structures monitoring.

3. Requirements for CPS-based TSM

A useful system requires the developer to first of all understand how the developed system is expected to work by end users. Therefore, before comprehensive system design and development, the system requirements of the proposed TSM were analyzed and summarized based on the identification of end user requirements.

3.1. End user requirements identification

The CPS-based TSM system is targeted at assisting construction workers, safety inspectors and project managers with the safety management of temporary structures. The user requirements are identified through the review of literature and accident reports published by OSHA. These user requirements are further adjusted and confirmed through interviews with three professionals in charge of safety management on construction jobsite conducted as a part of this research. Based on the interviews, several key requirements are identified as follows:

- **Functionality.** In general, the CPS-based TSM should be able to identify the most frequently occurring structure failures incorporating a clear user interface and limited errors. For active control of temporary structures monitoring, the end user should be granted some freedom in setting the level of hazards to be tracked. Close communication between the virtual model and the actual physical temporary structures, as well as between humans and CPS-based TSM system are required.
- **Real time inspection.** The dynamic construction environment highlights the importance of continuous and real time inspection of potential hazards. It is recommended by the end users that an effective temporary structure monitoring system should keep an eye on the performance of temporary structures as frequently as possible.
- **Early warning.** It is commonly known that prevention of potential failures is much more important than discovery after actual collapse. In the hope of avoiding potential failures of temporary structures, it is required to have an early warning so that potential problems can be corrected before actual accidents occur.
- **Immediate instruction to construction workers.** Based on the working experience of interviewees contacted as part of this research, it is more important for construction workers, rather than safety inspectors and project managers, to receive immediate instructions and warnings. Due to the urgency of potential hazards, the construction workers are expected to take corrective action or get away from the dangerous working zones immediately. As is indicated by the interviewees, there is commonly an absence of proper management when safety professionals are away from the construction jobsite while potential failures of temporary structures occur. This delayed safety management can lead to serious accidents.
- **Simple and clear.** For safety concerns, the use of CPS-based TSM should be simple to use and the information sent to the end users should be easy to understand. In concern for the education background of some construction workers, a simple system can be promoted more quickly and used correctly. Besides, the simple and clear feature of TSM also assists safety inspectors and project managers in safety management without the need for special or extensive training programs.
- **Nonintrusive to daily work.** Portable monitoring or warning devices should be wearable and nonintrusive to the work on a

construction jobsite. While the construction workers are working at the jobsite, it would be impossible for them to carry any large devices, which may be inconvenient or cause damage rather than preventing potential dangers to workers.

- **Remote interaction.** To obtain immediate notification and updated information for safety inspectors and project managers, the developed TSM should enable remote interaction between the temporary structures on the construction jobsite and safety inspectors and project managers anywhere, even when they are far away from the construction jobsite. Remote interaction is also important when there are serious structural deficiencies that are out of the control of the project manager and need immediate input from structural engineers. In other words, it would be beneficial if structural engineers could get remote access to the structural performance of the temporary structures for structural analysis and problem diagnosis.
- **Accuracy and trustworthiness.** On the construction jobsite, even a small change or difference in the structural performance may lead to tremendous failures. Therefore, it is important to have an early detection and resolution of the potential problems. For example, the change of inclination of a vertical component should be identified within one degree.

3.2. System requirements

In view of the end user requirements above, and the available IT-based methods, the system requirements of a CPS-based TSM are identified through the analysis of end user requirements and the key features of CPS. Details are discussed as follows:

- **Predefined system logic for inspection of most frequent structure failures.** This is intended for simple use by the end users with comprehensive temporary structures monitoring. The key failure patterns of temporary structures should be explored for the design of algorithms for potential failure identification. The predefined system logics also minimize the requirement of professional knowledge at the stage of operation, which make TSM a simple and easy tool for the end users.
- **User-defined threshold for potential hazards.** Along with the suggested threshold predefined according to relative safety regulations and manufacturers suggestions, for active management of temporary structures by the end users, the system should provide the end users access to the CPS-based TSM so that the threshold of potential hazards can be self-defined, when more stringent requirements are necessary or desirable.
- **Real-time and remote communication.** To enable real time and remote interaction between temporary structures and their virtual models, continuous wireless connections must be set up. Since the temporary structures work in the dynamic construction environment, the inspection of the temporary structure should be in real-time (within a specified time period), so that potential structural defects can be quickly identified and an early warning issued before actual accidents occur.
- **Portable and wearable devices to receive warnings and instructions.** Devices carried by construction workers should be small enough to be carried without affecting their daily work activities. In addition, instead of just a simple alarm without information about what is going on, the wearable devices should be able to provide clear information on potential hazards to notify construction workers where the problems are, and to provide safety inspectors and project managers with detailed information for decision making.
- **Visualization.** Good visualization provides clear understanding of the potential problems. The requirements of visualization include two aspects visualization of the temporary structures and the visual presentation of response instructions. The virtual model of temporary structures is one of the basic systems of CPS, which provides user interfaces for remote inspection and control of the physical model. The virtual model consists of digital components with unique IDs that can be recognized independently by the computing system. It is important that the virtual model provides basic properties and information on the temporary components, which assists professionals in structural analysis and decision making in preventing potential collapse. Besides, to avoid misunderstanding, the instructions, along with the picture identifying the components in question should be presented clearly to workers.
- **Data precision and resolution.** The structural analysis of temporary structures has a high requirement for data accuracy and resolution, because of the potential for failures due to the dynamic construction environment. In practice, there is always system error and signal noise along with the observed information. The high requirement of data accuracy calls for an appropriate data processing method 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 [24], so that more detailed structural performance of temporary structures can be captured.

4. System development

First of all, the system architecture of CPS-based TSM is discussed, followed with a description of the system development environment. Finally, the developed TSM is presented with details of the system operation, demonstrating how the system works in preventing potential structural failures.

4.1. System architecture

Generally, the proposed CPS-based TSM system consists of physical structures and their virtual models, which are integrated through a CPS bridge supported by a communication network and database. The system architecture is demonstrated in Fig. 1 and described below:

- **Physical structures:** the physical structures are the ones discussed in Section 1, and include both the temporary support systems (such as scaffolding systems and formwork) and temporarily used structures (such as temporary performance stages).
- **Virtual model:** the virtual models are the virtual representations of the physical structures described above. The virtual models can be developed using 3D/4D virtual prototyping software.
- **Cyber-Physical Bridge:** the Cyber-Physical Bridge enables the information exchange between the physical structures and the virtual models. The Cyber-Physical Bridge is supported by the communication network and an on-cloud database.
- **Physical-to-Cyber Bridge:** real time information on physical structures is collected using data acquisition systems (DAQ) and transmitted to the cyber system via the communication network.
- **Portable devices:** the portable devices are used as communication tools between the TSM system and construction site

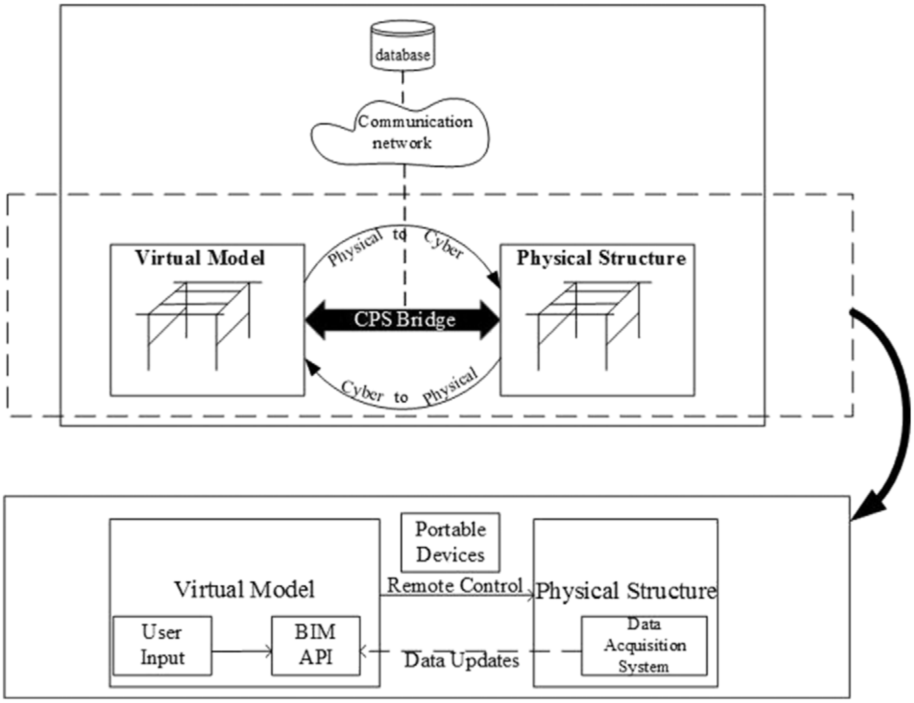


Fig. 1. System architecture of CPS-based TSM.

personnel who may need to adjust or manipulate the physical structures based on the instructions from the virtual model.

4.2. Choice of development environment

The selection of the system development environment involves identification of hardware and software environment for developing the prototype system. Both of these work together as the development platform for the CPS-based TSM system.

4.2.1. Hardware environment

The hardware environment provides the equipment required for system development or simulation. Examples include a set of temporary structures, sensors for structural performance monitoring, and portable devices for communication between TSM and construction workers.

- **Temporary structures.** While there are various types of temporary structures, the scaffolding system has been selected as an example of the CPS-based TSM for two reasons. First of all, scaffolding systems, ranking third among top 10 OSHA violations in the year of 2013, account for a large number of fatalities and injuries in the construction industry [18]. Secondly, the principles of structural monitoring for scaffolding systems are similar to those of other types of temporary structures, which indicates that the TSM of scaffolding system can be easily adapted for other temporary structures. Therefore, one of the most commonly used scaffolding systems, a simple set of frame scaffold (5 ft × 5 ft × 7 ft), as shown in Fig. 2, was set up in the laboratory for system testing. This scaffold consists of two 5 ft × 5 ft scaffold frames and two sets of 7 ft × 4 ft cross braces. Six OSHA certified wooden scaffold planks were placed at the top of the scaffold frame, to provide a working platform to support workers or materials.
- **Sensors.** In order to detect the structural performance of the scaffolding system, four main types of sensors are adopted for data acquisition; these include load cells, switch sensors, an accelerometer, and a displacement sensor. The locations of the various sensors, as shown in Fig. 3, were carefully determined by taking into account the required information for analysis, data accuracy, requirement of sensor installation, and sensor sensitivity. In particular, for loading purposes, the load cells are placed under the posts so as to collect information on the loading placed on each scaffolding post; and switch sensors are attached by the side of the bases of the scaffolding system, with their connectors touching the steel plates, which are used to simulate the ground surface. Once there is movement that results in a disconnection between the connector and the steel plate, a signal is initiated by the switch sensor indicating the occurrence of significant base settlement. Accelerometers are attached on the upper side of posts for inclination and movement information of scaffolding posts; a displacement sensor is mounted under one of the planks in the middle, where the worst displacement of a plank may be detected under pressure. It is connected at the bottom of the plank with an inserted screw for a solid connection.

  In general, the load cell can withstand and detect up to 2000 pounds of load placed on it with a resolution of 1 pound. It helps to identify the amount of load supported by or distributed to each scaffold post. The load cell produces a positive signal when the post is pulled up from the load cell, and a negative signal when there is pressure from the post onto the load cell; the switch sensor works with a maximum switching frequency of 2 Hz, providing the signal that indicates when there is a significant base settlement of the scaffold system. It works in such a way that the signal is “off” when the body of the switch is attached to the ground surface, and turns to be “on” with a minimum distance of 0.5 in. between the body of the switch sensor and the ground surface; the accelerometer has a sensitivity of 100 mV/g with a measurement range of ±50 g pk. It is used to measure the rate of change of movement and can be used to confirm inclination of the scaffold; the displacement sensor helps to monitor the displacement of the scaffold planks

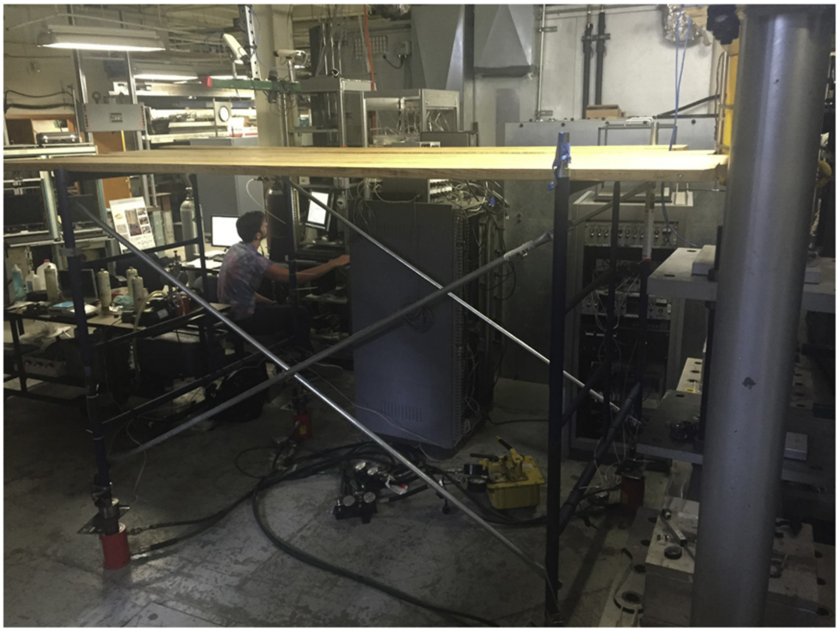


Fig. 2. Frame scaffold set.

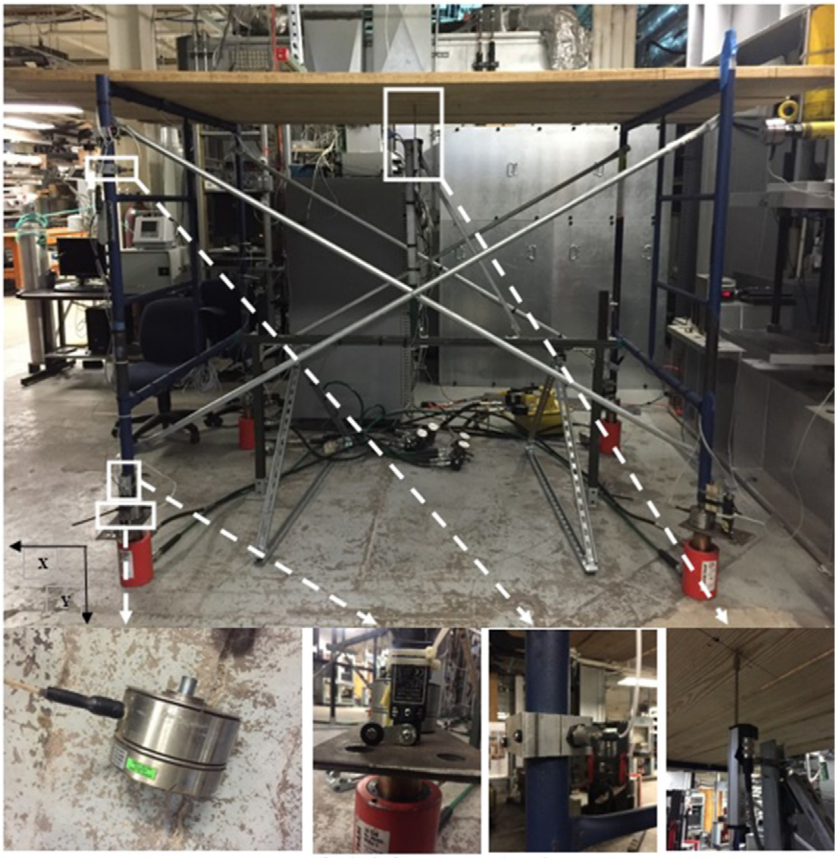
under pressure. It can detect up to 4 in. displacement with a resolution of 0.001 in. All of the information is sent to the data acquisition system and stored in the database for structural performance analysis. Based on the users requirements, other types of sensors can also be incorporated.

- **Portable devices.** In this study, a smart phone running android operating system is used as the portable device for construction workers, safety inspectors, and project managers. The idea of using a smart phone is to provide the end users information from the CPS-based TSM without requiring additional devices. However, the end users are not restricted to the smart phone for safety inspection of temporary structures. For the users convenience, other smart devices (such as tablet devices and smart watches) may also be used, as long as the operating system is compatible with the developed TSM system.

4.2.2. *Software environment*

The development of CPS-based TSM involves the integration of several systems, including the communication network. In general, the core system is built as a plug-in of Autodesk Navisworks Management, which provides the user interface for end users. This plug-in relies on data collection systems and data communication through a communications network. The choice of each system is analyzed below:

- **Virtual model and plug-in system.** Emerging BIM software provides a variety of choices for visualization of temporary structures, such as Autodesk Revit and Autodesk Navisworks Management. These software provide an open .NET application programming interface (API), which provides an extendable user-defined application that can trigger system operation from outside the user interface. However, compared to Revit, Navisworks provides more freedom to developers in managing the properties of virtual models, which is highly necessary in the TSM based on the system requirements. Therefore, Autodesk Navisworks Management was selected for the development platform of the virtual model and plug-in system.
- **Data collection platform.** Given National Instruments hardware used for data acquisition from the physical mock-up of the temporary structure, its associated system design platform, which is called Lab view, was used as the data collection platform. Lab view provides extensive support for interfacing with a variety of devices, such as sensors and cameras. It also has a large number of functions related to data acquisition, signal conditioning, and a GUI (Graphical User Interface) for quick and stable data acquisition.
- **Communication network between PC and portable devices.** In this context, there are three main methods of communication: point-to-point communication, cloud computing service, and text message by setting up a virtualized sever which sends text message of alarm to cell phones when potential hazards appeal. While it is easy to set up point-to-point communication, it requires the setup of a router and server at the DAQ control system. Besides, this communication method requires a change in IP address every time another computer is used. The use of text messaging avoids the development of application at the portable devices, yet it serves more as a passive warning system with limited information and little interaction from construction workers. Besides, a text message can be easily ignored by construction workers for it only provides one alert/notification, which is not different in sound to other text messages. The use of cloud computing services was identified as the most appropriate communication method for this CPS-based TSM for two main reasons. First of all, the cloud computing service provides a stable and quick communication network between different systems on several devices from different locations without changing settings, such as the IP address. It also provides a larger database, which can be extended and restructured for more complicated applications, such as the storage of historical record of each identified potential hazards during construction.
- **Database management system.** Heidi SQL, also previously known as MySQL-Front, was utilized to manage the on-cloud SQL from local computers. Heidi serves as a simple and open client for database management. It provides a useful and stable way to edit data, create tables and export data. Besides, there



Load Cell **Switch Sensor** **Accelerometer** **Displacement Sensor**

Fig. 3. Layout of sensors.

is a free version of Heidi SQL, which can be used at no cost to the developers.

- **Development platform for portable devices.** While both IOS and Android platforms are available for mobile app development, the IOS platform only provides a closed source, which means that the developed app can only be used on specific types of devices. On the contrary, the Android platform provides open source which enables mobile apps to be used on any devices. To enable most of the construction workers and safety inspectors to use the CPS-based TSM, the android platform was selected for mobile app development.

4.3. CPS-based TSM system development

The CPS-based TSM system was developed based on the hardware and software environment identified above. The key steps of system developments include the development of the 3D virtual model, plug-in system, on-cloud database, and mobile app. Details of each development step is presented as follows:

4.3.1. 3D model and plug-in development

A 3D model of the frame scaffold system was initially developed in Autodesk Revit 2015, as shown in Fig. 4. This Revit model was then imported into Autodesk Navisworks Management 2015 for further modification. To make the virtual model look more realistic compared with the real scaffolding set and to distinguish the various elements, the color of each component was adjusted, as shown in Fig. 5.

The plug-in for CPS-based TSM, was then developed and launched as an add-in tool shown at the Autodesk Navisworks Management 2015. In doing this, the plug-in program was initially developed and compiled using Microsoft Visio Studio, and saved at the specified document address to be triggered by the software of Autodesk Navisworks Management every time the software is opened. A GUI was developed for user input and interaction. Also, a user input form was created and saved as a text file at local computer so that the plug-in system can remember the latest user input without the need to re-enter it every time the plug-in is opened.

After entering the user input, the CPS-based TSM starts inspection once the start button is clicked. Every 2 s , the TSM will collect

Fig. 4. Revit model of frame scaffold.

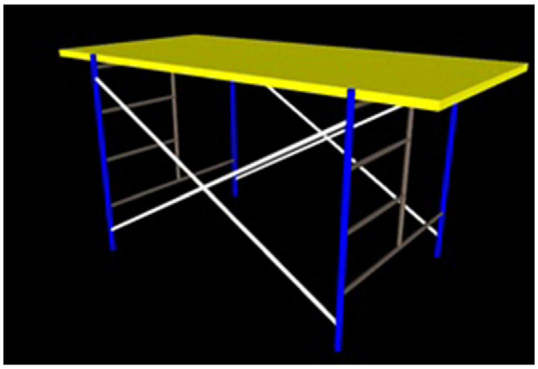


Fig. 5. 3D model of scaffold in Navisworks.

updated data from the database and identify potential structural failures. It works by post processing the updated information to the required format and compares it to a set of limitations, which is also known as the user-defined threshold for potential structural hazards. Once there is potential for structural failure, the components in question will be highlighted in the virtual model, and a warning notification is sent immediately to the mobile app of TSM installed at portable devices (as shown in Fig. 6).

4.3.2. *On-cloud database for bi-directional communication*

Generally, an on-cloud database is a database that typically runs on a cloud computing platform via the Internet [32]. An on-cloud database is necessary to the development of the CPS-based TSM system for three main reasons. First, the cloud database enables remote inspection of the physical structures from the virtual model via the Internet. Secondly, multiple users can gain access to the TSM system via the Internet for real time inspection and data analysis; Third, as has been discussed in Section 4.2.2 on communication network between PC and Portable Devices, the communication between the virtual model and the mobile app is supported by the on-cloud database.

In view of the above, an on-cloud database was developed for this study using the Amazon Elastic Compute Cloud (Amazon EC2) service (as shown in Fig. 7), whose SQL database can be edited and managed through Heidi SQL at local computers (as shown in Fig. 8). According to the information types processed in the database, three main types of services are adopted in Amazon EC2, including a MySQL database, a Linux File System, and GCM (Google Could Messaging) service. First of all, the on-cloud SQL database serves as the storage of the updated information from physical structures and read by the CPS-based TSM for structural performance analysis. Based on the structural information required for structural performance analysis, a table with the name and structural information of each scaffolding component was established and can be maintained through Heidi SQL, as shown in Fig. 8. Generally, the information to be collected for the four posts includes the change of two directional inclinations (see orientation in Fig. 3), "loading" and "base connection". A similar database structure is used for storing information on the scaffolding planks. In particular, the negative value of loading indicates downward force, while the positive value indicates upward force between the post and the load cell. Taking the initial experimental test for example (see Section 4.4.3 on "Experimental test of base settlement" for details), when post 3 is lowered 1/8 in. , the corresponding information recorded in database is shown in Fig. 8. It can also be seen that post 1 has a change of inclination of 1.8° in y direction and 1° in x direction; the load pressure recorded at post 1 is 22 pounds downwards (indicated with the value of "−22" in the database); the base of post 1 is well connected (indicated by the value of "1" for "base connection" in the database). Secondly, a Linux File System provides the storage of pictures from the TSM controlling system once potential hazards have been identified and can be accessed within 2 s by the TSM mobile app installed on portable devices. Last, a GCM service is used to push alarm notifications to portable devices. It allows multiple registered portable devices to remain inactive until a potential hazard has been identified. The benefits of the GCM service include the economical use of the battery power of portable devices, easy access to alarm notifications by multiple portable devices at the same time, and real-time potential hazards information.

As seen in Fig. 7, the structure and work flow of the on-cloud database has been identified. To be specific, first of all (noted as step 1 in Fig. 7), the real time information of physical structures is updated and stored at the MySQL database; second (noted as step 2), this updated information of physical structures is continuously fetched by the cyber system for safe structure analysis; third, once potential hazards are identified, the picture of the virtual model with components in question highlighted is uploaded to the Linux file (noted as step 3.1) with relative information uploaded to MySQL database simultaneously (noted as step 3.2); meanwhile, the GCM queries the MySQL for potential alarm information every 100 ms (noted as step 4); the frequent query ensures that once there is alarm, the GCM sends alarming notification to portable devices (noted as step 5); Finally, portable devices fetch pictures of virtual models from Linux file (noted as step 6.1) and alarming instructions from MySQL (noted as step 6.2), which are previously uploaded by the Cyber system.

The use of Amazon EC2 service also enables scalable applications of TSM if needed. For example, a more comprehensive analysis of the potential hazards can be obtained through machine learning of the detailed historical record of not only structural performance but also other related information, such as temperature and workers health status, to be stored in the on-cloud database.

4.3.3. *Mobile app for human-machine interaction*

An android mobile app, named TSM, was developed and installed on a smart phone, as shown in Fig. 6. Every 2 s , the mobile app checks if there is any warning or instruction sent from the TSM system.

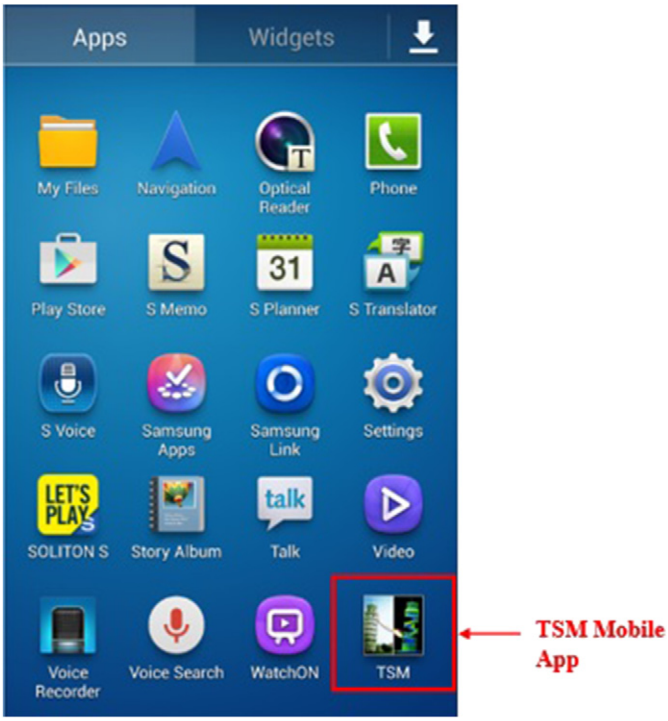


Fig. 6. Mobile App of TSM.

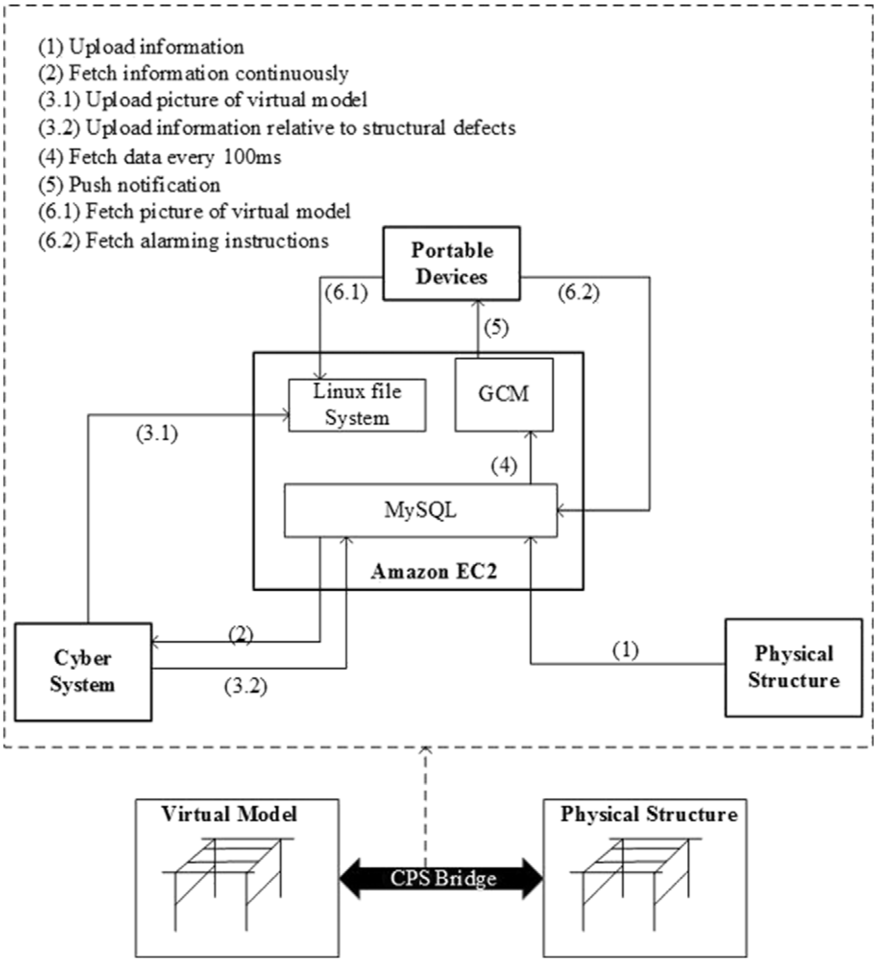


Fig. 7. Structure of on-cloud database.

Once a warning or instruction is received, the mobile app is automatically activated with alarms that will keep ringing until responded to (tap the notification message) by the end users. Once the notification message of TSM app is clicked, the app is opened with a picture showing the virtual model with the components in question highlighted, so that the end users have a direct understanding of the location of potential problems. Meanwhile, a text message notifying the problem is shown at the bottom of the picture. More detailed information on the structural problems of each component can be obtained by tapping the detail button.

4.4. *System operation*

For better understanding of how the CPS-based TSM works, the system workflow is presented below, followed by the experimental test of the base settlement of a frame scaffold set.

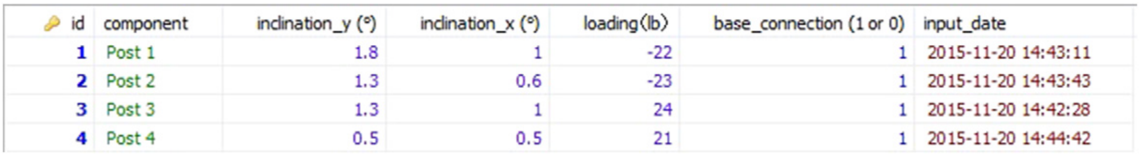
4.4.1. *System workflow*

Generally, the CPS-based TSM works as summarized in the key steps shown in Fig. 9 and described below.

1. The structural information of the temporary structures, such as inclination and loading, is collected by the sensors discussed in the Section 4.2.1 on sensors and sent to the DAQ platform;
2. information on temporary structures is post processed through Lab-view and sent to the on-cloud database every 2 s;
3. the CPS-based TSM queries the on-cloud database every 2 s for structural performance analysis based on predefined system logics;
4. if no potential hazard is identified, the TSM continuously collects performance information through sensors attached to the temporary structures. However, if potential for structural failure was identified by TSM based on performance analysis, the component in question will be highlighted in the 3D virtual model for further investigation or adjustment. Meanwhile, the warning and detailed information of structural performance deficiencies is sent from the virtual model to portable devices used by construction workers, safety inspectors, and project managers;
5. finally, assisted by the useful information associated with the structural deficiency, the end users are able to take appropriate action to address the problem and thus prevent structural failure. In this way, the CPS-based TSM works continuously following the system workflow discussed in this section, and which supports real time monitoring of the actual performance of temporary structures.

4.4.2. *TSM user interface*

As shown in Fig. 10, the CPS-based TSM interacts with end users through the developed add-in tool in Autodesk Navisworks Management named CPS Monitor. The right window displays the virtual model of temporary structures, and provides a clear view to the end users. Once the tool button of CPS Monitor is clicked, a window for



id	component	inclination_y (°)	inclination_x (°)	loading(lb)	base_connection (1 or 0)	input_date
1	Post 1	1.8	1	-22	1	2015-11-20 14:43:11
2	Post 2	1.3	0.6	-23	1	2015-11-20 14:43:43
3	Post 3	1.3	1	24	1	2015-11-20 14:42:28
4	Post 4	0.5	0.5	21	1	2015-11-20 14:44:42

Fig. 8. Database for base settlement at initial stage viewed from Heidi SQL.

user input of warning threshold and Log pops up. As is shown, the value of the threshold will be the one entered last time, and can be edited by users at any time before starting the structural inspection. Once satisfied with the warning threshold, end users can click the start button to run the CPS-based TSM. In the background, the system evaluates the structural performance of temporary structures every 2 s with updated information from the physical temporary structures. The response of the TSM to the potential failures is designed as two-fold. First of all, for the end users working in front of the computer, the 3D model will highlight the components in question for the users attention, and display how the TSM is communicating with the portable devices to make sure the construction workers and other safety inspectors on the construction jobsite have been notified of the potential hazards (as shown in Fig. 10).

4.4.3. Experimental test of base settlement

As identified by Whitaker et al. [33], base settlement ranks as one of the key causes of scaffolding accidents. For system operation demonstration, an experiment on the base settlement of the frame scaffold was conducted for two stages: initial stage when there are potential basement settlements at post 3 and second stage when actual basement settlement occurs at post 3.

1. **Initial stage.** The initial stage is the situation when there is a trend of base settlement before actual significant settlement occurs. This is simulated by lowering the base of post 3 by up to 1/8 in. Once the warning threshold for each component has been entered and verified in the threshold window (as shown in the left side of Fig. 11), the start button is clicked to run the TSM system for real time inspection. It is noticed (as shown in Fig. 8) that all the four posts inclined. Meanwhile, the loads recorded at the bases of post 3 and post 4 become positive, indicating that the post 3 and post 4 are moving up against their bases. In 2 s , post 3 and post 4 were highlighted immediately as the deficient components in the virtual model, as shown in the right side of Fig. 11. Besides, the Log (shown in the left side of Fig. 11) indicates that a warning has been sent to the mobile App TSM (as shown in Fig. 12). A picture which highlights the affected component is displayed on the mobile App of TSM, along with messages (as shown in the left side of Fig. 12). For more detailed information, supervisors can click on the details button to display a check list that specifies how each component is performing (as shown in the right side of Fig. 12). In this way, supervisors understand immediately that there are potential base settlements at post 3 and post 4. By checking these posts in the physical environment, supervisors can take corrective action or report to the project manager for further investigation.

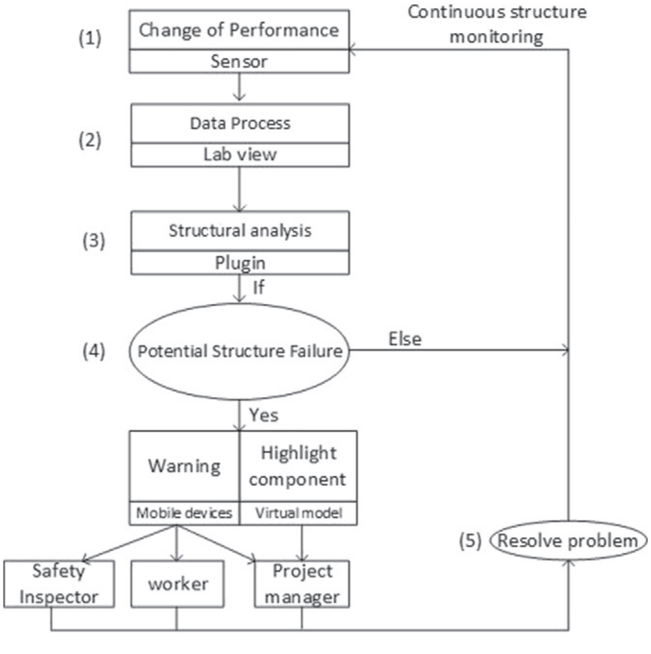


Fig. 9. System workflow.

2. **Second stage.** In case the potential base settlement at the initial stage is not prevented by supervisors, the second stage indicates the situation when the base settlement of post 3 actually happens as defined by complete separation of the post from the foundation support. This is simulated by lowering the base of post 3 up to 2 inches. At this point, there is a disconnection signal from the switch sensor placed at the base of post 3, along with increasing negative loading information at the base of post 3 and post 4. The imbalanced loading distribution happens due to the severe inclination of the whole structure. The actual danger of post 3 and potential problem of post 4 are updated immediately in the virtual model, with the component with the actual problem (post 3) highlighted in purple color and one with potential hazard (post 4) in red color, as shown in Fig. 13. Meanwhile, warnings and instructions are also sent to the supervisors.

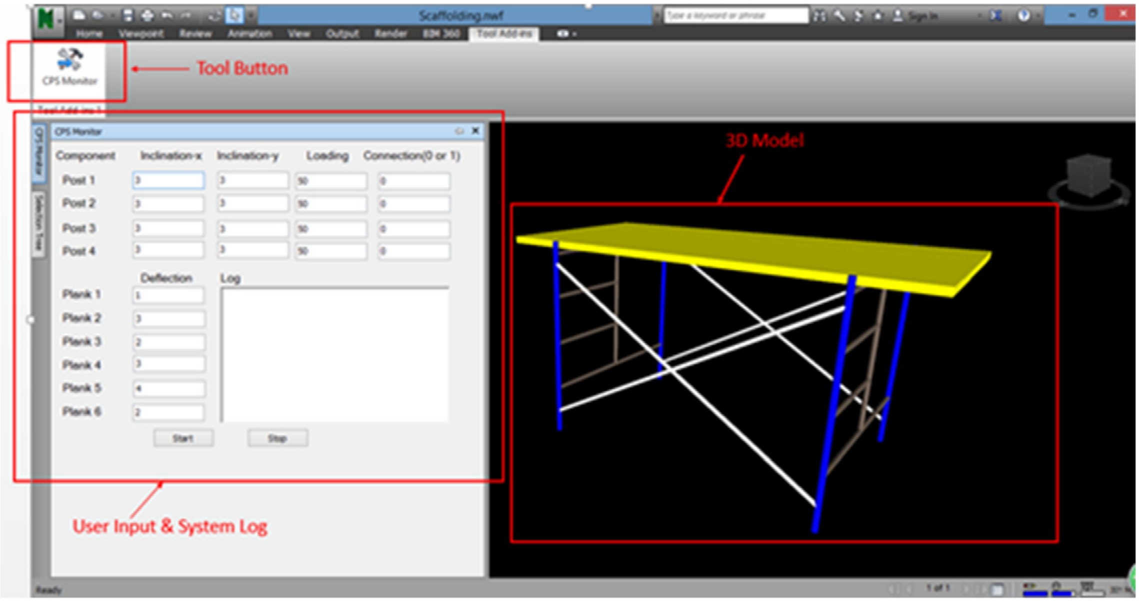
5. Potential benefits and limitations of TSM

Based on the key features and applicability of CPS to temporary structures, CPS-based TSM prototype system development and the experimental test, several potential benefits and barriers to TSM implementation are identified as follows:

5.1. Potential benefits

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

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



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

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

Log

Fig. 10. User interface of CPS-based TSM.

- **Tight coupling of physical components and virtual model:** CPS-based TSM enables bi-directional communication between physical components and their virtual representations. Through the Physical-to-Cyber Bridge, the movement of physical components are tracked by sensors and sent to the virtual model, where the difference between the designed and actual structure are analyzed and compared with acceptable thresholds, with distressed components being highlighted in the model. Through the Cyber-to-Physical Bridge, once potential hazards are detected, safety alerts or corrective instructions can be sent from the virtual model to the workers.
- **Remote and multi-party access for management:** due to the bi-directional information loop between the physical and virtual components, the structural performance of temporary structures can be remotely monitored through virtual models. CPS-based TSM enables multiple parties to obtain access to the structural monitoring system from different locations through the virtual model interface. This function benefits project managers, structural designers, owners and other parties involved in routine structural monitoring by facilitating real-time potential structural problem analysis, avoidance of potential dangers, and enhanced collaboration.
- **Early warning with customized safety level:** implementation of a CPS-based TSM 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 structural failures have already occurred, an early warning would be sent once there is a reasonable risk of potential structural failure. The safety factor can be used as recommended or customized if the user wishes to have a higher level of safety.

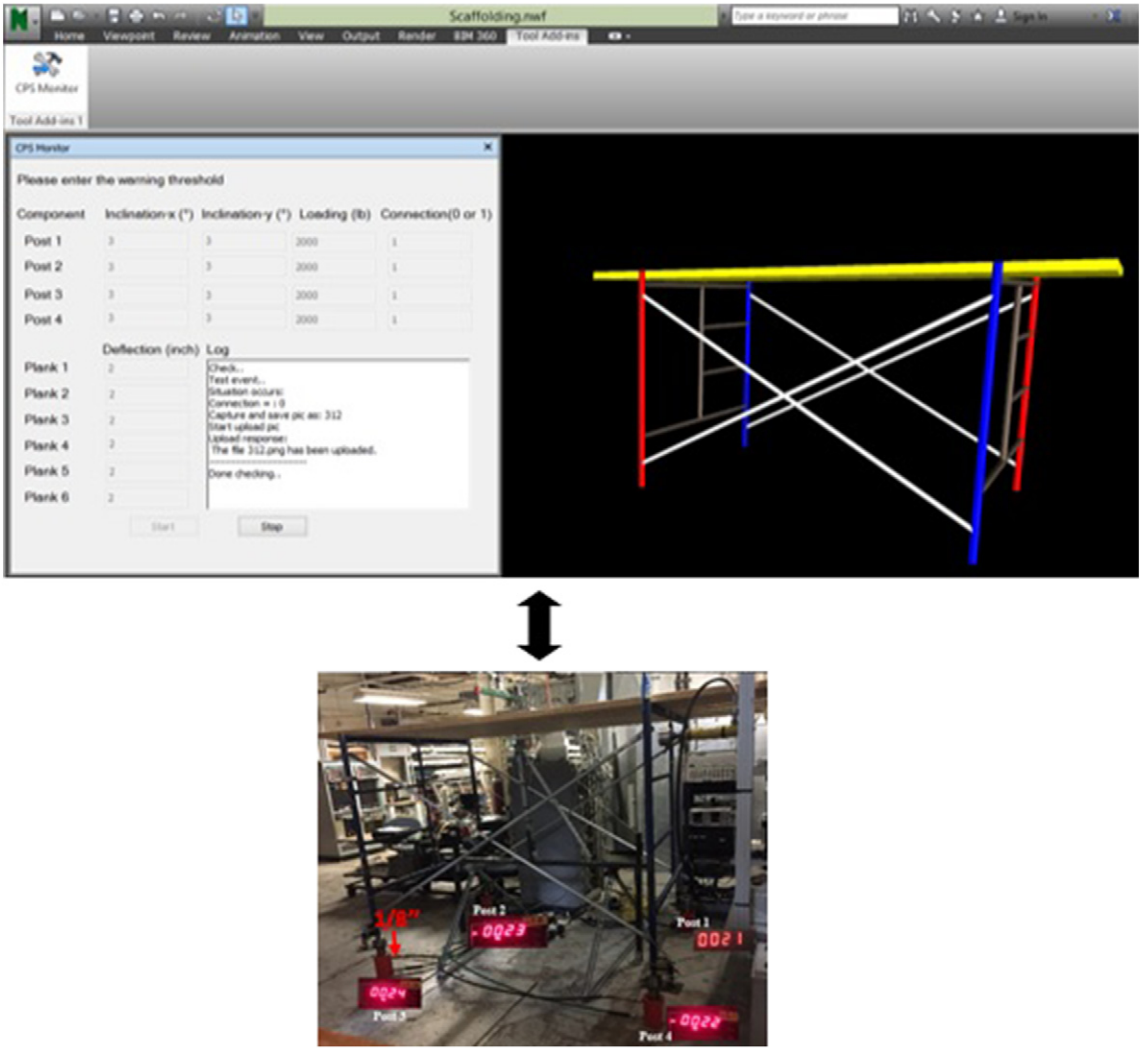
5.2. Potential barriers to TSM implementation

The preceding discussion has described the benefits of CPS implementation for the monitoring and performance of temporary structures. However, there are also barriers and technical issues to be addressed in order to maximize the realization of these benefits. 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 a commercial business or hospital environment might impair the security of personal information [34].
- **Reliability:** Random failures in TSM 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 [31]. However, modern construction job sites involve numerous kinds of electronic equipment which impact the accuracy of sensed signals. Physical damage to a sensor due to construction operations or impact is also a possibility.
- **Training of workers:** CPS-based TSM involves the management and installation of new technologies, including hardware such as sensors on job sites. These technologies need to be implemented, tested and inspected on a continuous basis. Thus, it is imperative that construction personnel are adequately trained in the use of these new technologies.
- **Financial issues:** although the price of sensors continues to drop, accurate monitoring of temporary structures and early identification of potential problems requires a large number of sensors to work simultaneously. In addition, the use of portable devices, the maintenance of communication networks, and the training of workers have cost implications that will need to be addressed.

6. Conclusions

The construction industry remains one of the most dangerous industry sectors and urgently needs improvement. To be specific, the safety hazards relative to the failure of temporary structures has a significant impact on the overall safety performance of the construction industry. Emerging technologies such as CPS offer a promising



Please enter the warning threshold

Component	Inclination-x (°)	Inclination-y (°)	Loading (lb)	Connection(0 or 1)
Post 1	3	3	2000	1
Post 2	3	3	2000	1
Post 3	3	3	2000	1
Post 4	3	3	2000	1

	Deflection (inch)
Plank 1	2
Plank 2	2
Plank 3	2
Plank 4	2
Plank 5	2
Plank 6	2

Log

```
Check..
Test event..
Situation occurs:
Connection = : 0
Capture and save pic as: 312
Start upload pic
Upload response:
 The file 312.png has been uploaded.
------------------------
Done checking..
```

Fig. 11. TSM performance initial test of base settlement.

solution for advanced monitoring of temporary structures by providing real time communication between the virtual system and physical temporary structures. This study explored the applicability of CPS for temporary structures monitoring, identified end user requirements and system requirements, and proposed a CPS-based TSM as a method to prevent potential failure of temporary structures. A frame scaffold set was adopted as an example temporary structure for TSM system demonstration and evaluation. To date, the CPS-based TSM has shown promise in the real time monitoring of temporary structures.

6.1. Key conclusions

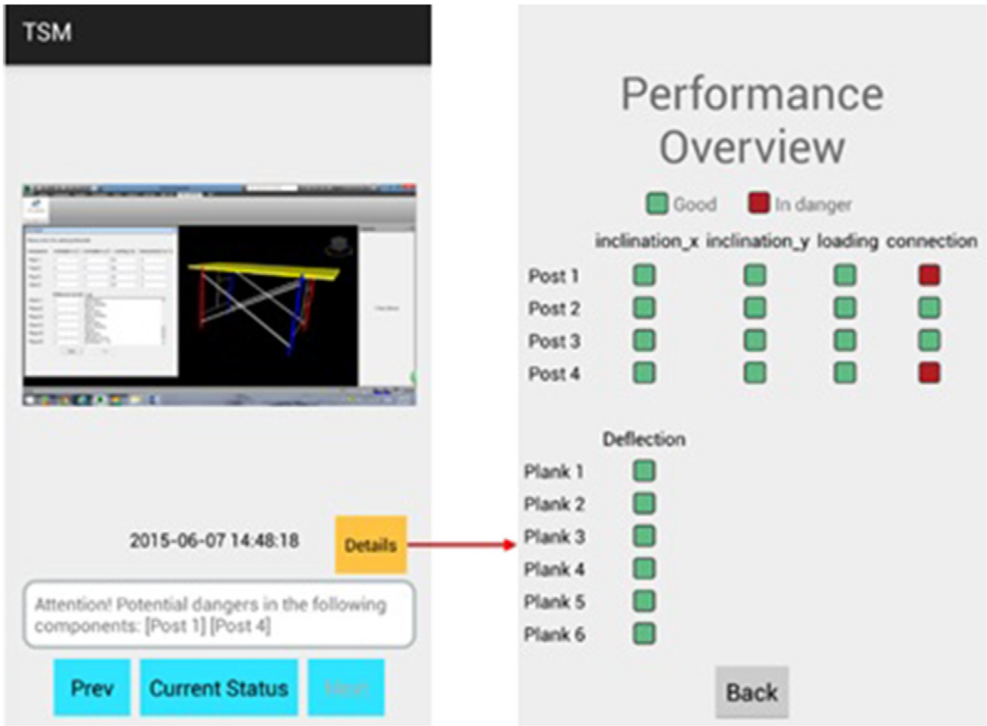
Several key conclusions can be drawn as follows:

- CPS offers 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.
- An effective TSM is required to provide real time inspection, remote interaction, early warning, and immediate instruction to construction workers. Besides, the use of TSM should be simple and nonintrusive to the daily work of construction workers.
- The development of CPS-based TSM involves the setup of hardware, such as the temporary structure, and the choice of an appropriate system development platform (including a virtual modeling system, communication networks, and a database management platform).
- Initial simulation of the CPS-based TSM prototype system has demonstrated that the proposed system works well in identifying potential hazards of temporary structures in a real time manner with active interaction with end users.

6.2. Further research

While the proposed TSM method has provided the solution to closely integrate the virtual model and the physical components of temporary structures for structural monitoring, more applications and extensible benefits can be gained based on it. Possible future trajectories for this research include:

- **Application of CPS-based TSM for practical site deployment.** Although the CPS-based TSM has been developed and validated for its applicability to safety monitoring of temporary structures through laboratory experiment, the



2015-06-07 14:48:18

Attention! Potential dangers in the following components: [Post 1] [Post 4]

Performance Overview

🟩 Good 🟥 In danger

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

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

Fig. 12. Warning on portable devices.

wired sensors utilized for the TSM in this research project would be time-consuming and error-prone, especially with the increasing number of sensors in the real world. There is the need to adapt the monitoring and alert system to cope with the practical constraints of a busy construction site. For example, the use of wireless sensors or cameras as a means of data collection for TSM. The alert mechanism also needs to be tailored to be audible and visible in a construction site environment.

- **An Internet of Things (IoT) approach to linked temporary structures monitoring.** Building on the CPS-based TSM system, the interdependencies between temporary structures can be analyzed for safety purpose using an IoT approach. The approach of IoT also enables the communication among individual temporary components, which provides potential benefits such as improved construction coordination, construction site layout monitoring, and structural failures control.
- **Knowledge-rich TSM identifying causes to failures and recommendations.** During the monitoring of temporary structures, all the information on the temporary structures performance and system instructions under various conditions are recorded in the database. The relationship between instructions and structural problems can be learned and identified, which enables CPS to predict causes to problems, and provide suggestions for instructions when similar structural problems occur in the future.
- **Automatic control of temporary structures failures.** A comprehensive application of CPS enables the use of actuators which are placed on the temporary structures on the construction jobsite and behave according to the system commands. The use of actuators can provide an automatic control method for immediate safety adjustments without excessive human interactions.
- **Optimized emergency exit fuide in 3D map.** Future application of portable devices can be utilized for location identification of each end user. By integrating the virtual model of temporary structures and the locations of each end user on the construction jobsite, the TSM system provides not only the identification of deficient structural components, but also the person that works in danger near the temporary structures in question. Besides, instead of requiring workers to get out of the construction jobsite without clear direction when there's an

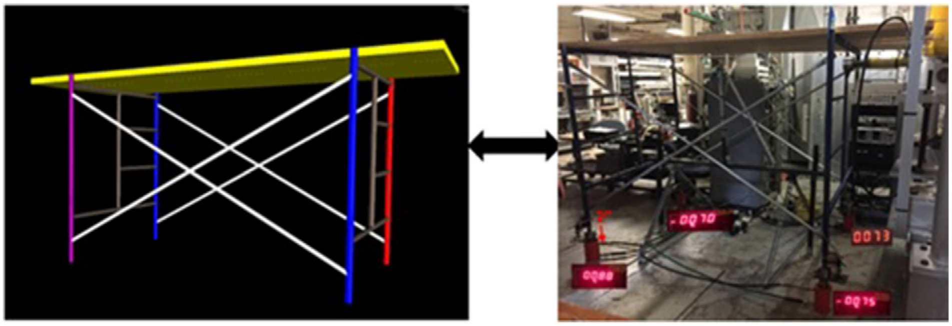


Fig. 13. Test of base settlement — second stage.

emergency, the location-based TSM can provide optimized exit guidance in 3D map by identifying the shortest safe exit route without getting into the area of potential failures.

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