A Framework for CPS-Based Real-Time Mobile Crane Operations

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Abstract

Construction machinery have long been associated with high accident rates. Mobile cranes are widely used in construction projects and represent one of the main items of machinery that contribute to a large number of construction accidents. While many of these accidents occur due to inadequate planning and a lack of foresight on the potential hazards on site, few of the mobile crane safety issues have been well addressed. This study seeks to address this problem by leveraging the use of Cyber-Physical Systems (CPS) for planning and monitoring mobile crane operations on the construction site. A framework for a CPS-based approach is developed and the key components and enabling technologies are discussed. With a focus on how the virtual interface of the CPS approach was developed and how the system provides safety assistance in mobile crane operations, the modelling process and analytical algorithms are explained in detail. The capability of enhancing bi-directional communication and coordination between virtual components and their physical representations enables CPS to change the way mobile crane planning and monitoring could be done. By enabling pro-active planning and real-time monitoring of crane operations, CPS manages to provide rich multi-modal feedback to crane operators and workers on site, and thus, helps to reduce/avoid mobile crane failures and mobile crane-related accidents.

Keywords

Cyber-Physical systems (CPS) • Real-time • Mobile crane operations

78.1 Introduction

Over the years, there have been increasing investigations into the use of Cyber-physical systems (CPS). With the ability of integrating computation with physical processes, CPS creates a close relationship between the virtual and physical domains [1]. According to literature, CPS integrates physical devices such as sensors and cameras with virtual components to form a situation-integrated analytical system that responds intelligently to dynamic changes of the real-world scenarios [2]. The definition of CPS reveals its key characteristics: bi-directional coordination and real-time communication. CPS provides a platform for bridging the physical world with its virtual representations, as shown in Fig. 78.1. The physical to virtual bridge is the sensing process, which involves using sensors and data acquisition technologies to acquire information about components or phenomenon. The virtual to physical bridge represents the actuation process which shows how the sensed information affects the system [3].

CPS has yielded improvements in many disciplines, such as transportation [4, 5], health-care [6, 7], navigation and rescue [8, 9]. The successful application of CPS in other industries has attracted attention on how CPS can be applied in the construction industry and what potentially benefit it can bring about. Early attempts at implementing CPS in the construction industry include building energy management [10], construction component placement [11], temporary structures monitoring

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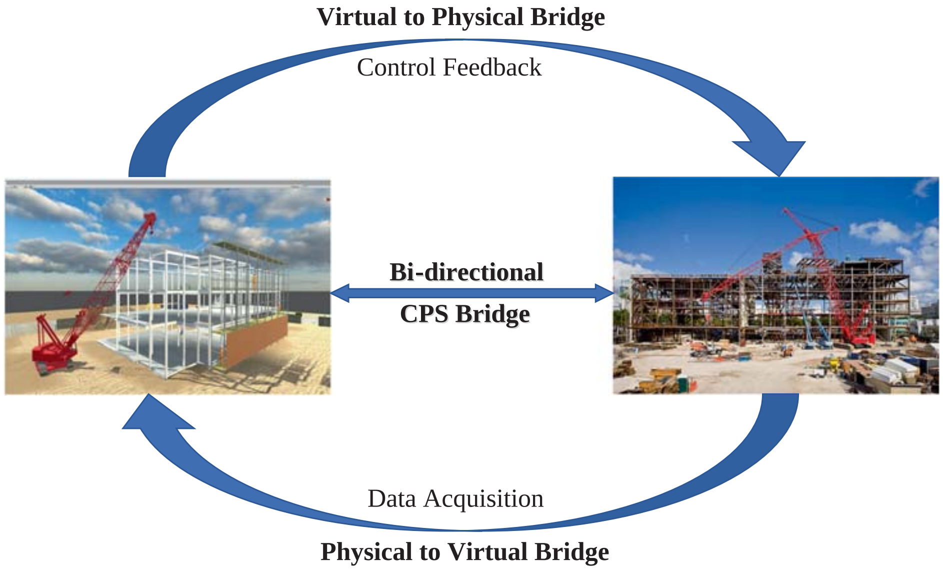
Fig. 78.1 A Bi-directional CPS approach



[12], and planning and monitoring of mobile crane operations [13]. In view of these applications, CPS has been identified as having substantial potential for addressing several problems within the construction industry, particularly given its emphasis on real-time interaction and coordination between the two system representations. It differs from traditional approaches which only monitor the physical world passively by bringing computational resources to bear in the physical world in an integrated fashion.

78.2 Background and Motivation

In the construction industry, machinery safety has long been criticized for being poor relative to other sectors and the associated severe consequences when accidents occur. Accidents caused by the operation of various machineries have posed serious problems as, once accidents occur, economic losses, occupational injuries and fatalities could be substantial [14]. It was reported that collisions, struck-by accidents, and rollovers caused by various machinery account for one quarter of the construction worker fatalities [15]. Cranes, as a central component applied widely in many construction projects, are associated with a large fraction of construction deaths. Construction fatalities in which cranes are involved account for up to one third of the total fatalities [16]. From 1997 to 2014, the number of fatalities in crane-related accidents totaled 566 for the construction industry, of which 306 deaths (54%) were related to mobile cranes [17]. Unlike tower cranes, which have a fixed location and operate within a limited workspace, mobile cranes move freely across a construction jobsite to perform the lifting tasks. Mobile cranes are considered to be riskier in nature than other types of cranes due to their on-site mobility [18].

Although numerous studies have sought to improve crane safety, and more strict regulations have come into effect, catastrophic crane accidents still occur. With the aim of providing real-time safety assistance for mobile crane operations, this paper presents a CPS-based approach to bi-directional communication and coordination between virtual crane models and physical crane operations on construction site. First, the key enabling technologies required for CPS integration of virtual models and physical construction site are outlined. Then, the CPS-based prototype system being developed for real-time mobile crane operations are described. The concluding part of this paper highlights the potential benefits and barriers in implementing the system.

78.3 Bi-directional Coordination in Active Monitoring and Control of Mobile Crane Operations

In this study, the bi-directional coordination involves linking the virtual mobile crane model as well as the site environment model with the corresponding physical site components. This is intended to enable the bi-directional information exchange and to facilitate the communication. The information to be exchanged include two aspects: (1) capturing the mobile crane movement data and site information (such as the location of essential site components and the building structure scheduled to be erected) from the physical interface, and (2) giving control feedback such as warning messages through portable audio devices to the workers and crane operator on site. The following sub-sections highlight the key enabling technologies used in enhancing the bi-directional coordination between virtual models and their physical representations.

78.3.1 Mobile Crane Motion Data Capture

Inertial Measurement Unit (IMU). An IMU is an electronic device assembled with a combination of accelerometers, gyroscopes, and sometimes magnetometers. It measures and reports a body's gravitational forces, angular orientation, and sometimes the magnetic field surrounding the body [19]. With the ability of tracking position changes and reporting inertial measurements, IMU is chosen to monitor the crane load position and sway.

Proximity Sensing System (iBeacon Technology). As one of the primary crane motions, the proximal location of the crane is measured by iBeacons. The iBeacon proximity sensing system is based on Bluetooth-based wireless sensing technology. It incorporates (1) Bluetooth signal transmitter, (2) mobile personnel receivers, (3) crane operator's receiver, and the software on which the system operates [20]. This iBeacon-based proximity sensing system is leveraged to locate mobile crane and to create a hazard detection area so that alerts will be sent to both the crane operator and the workers who enter that area.

78.3.2 Site Information Acquisition

To sense the updates on a construction jobsite, a combination of RFID tags and photogrammetry is proposed. RFID tags are proposed to be leveraged onto relatively small mobile objects which can be treated as a rigid body with fixed dimensions. Examples of such objects include vehicles and workers. For updates on site that require the dimensional data to be considered, photogrammetry is used. 3D geometrical data of such objects would be generated from the photo images. Examples include changes to the site layout such as bulk pieces of newly delivered materials, changes in the jobsite arrangement, and progress made on the building structure being erected. More details concerning site information acquisition can be found in [21].

78.3.3 Mobile Devices for Displaying Control Feedbacks

Mobile devices adopted in this study are portable computing devices which have a screen for displaying information. Examples of such mobile devices include tablet PC and Bluetooth enabled smart phones. A tablet PC is to be installed in the crane operating cab. It has a larger screen which can be used to navigate around the site model as well as the embedded data (such as warning messages triggered and site components which are subject to hazards) in the model. Tablet PCs also have built-in accessories such as Bluetooth signal scanner and RFID reader to capture data. Crane operators can easily use such a tablet to view crane motions and updates of the tagged site components. Smart phones are to be carried by construction workers equipped with RFID tags. Auditory warnings or haptic cues are conveyed to the workers to indicate hazardous behaviors and situations.

78.3.4 Communication Network

The communication network enhances bi-directional communication and coordination between virtual models and their physical representations by enabling the transfer and exchange of information between a tablet PC and local office computer. The communication network adopted in this study includes the Internet and wireless fidelity (Wi-Fi). Data captured on the physical site could be transferred through the communication network to the virtual model on the remote server. With the tablet PC connected wirelessly to the office computer, the status of the mobile crane can be viewed in the model at the office by the project team. In this way, bi-directional information exchange is achieved and the coordination between the virtual models and physical representations are enhanced.

78.4 System Architecture for Real-Time Mobile Crane Operations

The CPS concept is illustrated in the proposed system architecture in Fig. 78.2. The system architecture brings together the functionality and the key enabling technologies discussed previously as a framework for bi-directional coordination between the virtual models and physical representations. The architecture is based on five layers, which are explained in the following sub-sections.

78.4.1 Object Layer

The object layer consists of the physical mobile crane and the as-is site components. At this layer, different modules of a mobile crane and essential site components are identified for the sensing system to be leveraged onto so that the mobile crane movement data and as-is site environment data can be obtained.

Isolated Crane Modules. Mobile crane comes in a great variety of types and configurations. However, it can generally be seen as an entity which comprises several rigid bodies connected by joints [21]. Based on its operating mechanism, a mobile crane can be generally broken down into base, body, boom and load, as shown in Fig. 78.3. To capture crane movement data in real-time, a sensing system incorporating different types of sensors is adopted to measure the critical motions of different mobile crane modules.

As-is Site Condition. The as-is site information to be collected incorporates three parts: (1) geological site environment, such as the terrain and the trees, (2) site arrangement plan including the location of essential site components such as material stacks, site trailer, dumpster, and (3) the building to be erected. The afore-mentioned sensing technologies are to be leveraged on these site components to collect the as-is site condition data.

78.4.2 Sensing Layer

In the sensing layer, the initial crane position and as-is site condition are depicted through the sensing system proposed in the previous section. In addition to the as-is site condition, crane movements and changes on the physical site, such as progress on the proposed building structure, and movement of vehicles and workers are also tracked at this layer. The sensing system presented here was developed for a crawler lattice boom crane as shown in Fig. 78.4, but the application of the sensing system can be extended to other types of mobile cranes by using the same approach to break down the crane into modules as previously discussed. The sensing system collects crane motion information including (1) location of the crane, (2) location of the boom, and (3) location of the load. Sensors adopted for data acquisition include IMU sensor and iBeacons. The locations for sensor installation and the information they collect are shown in Fig. 78.4.

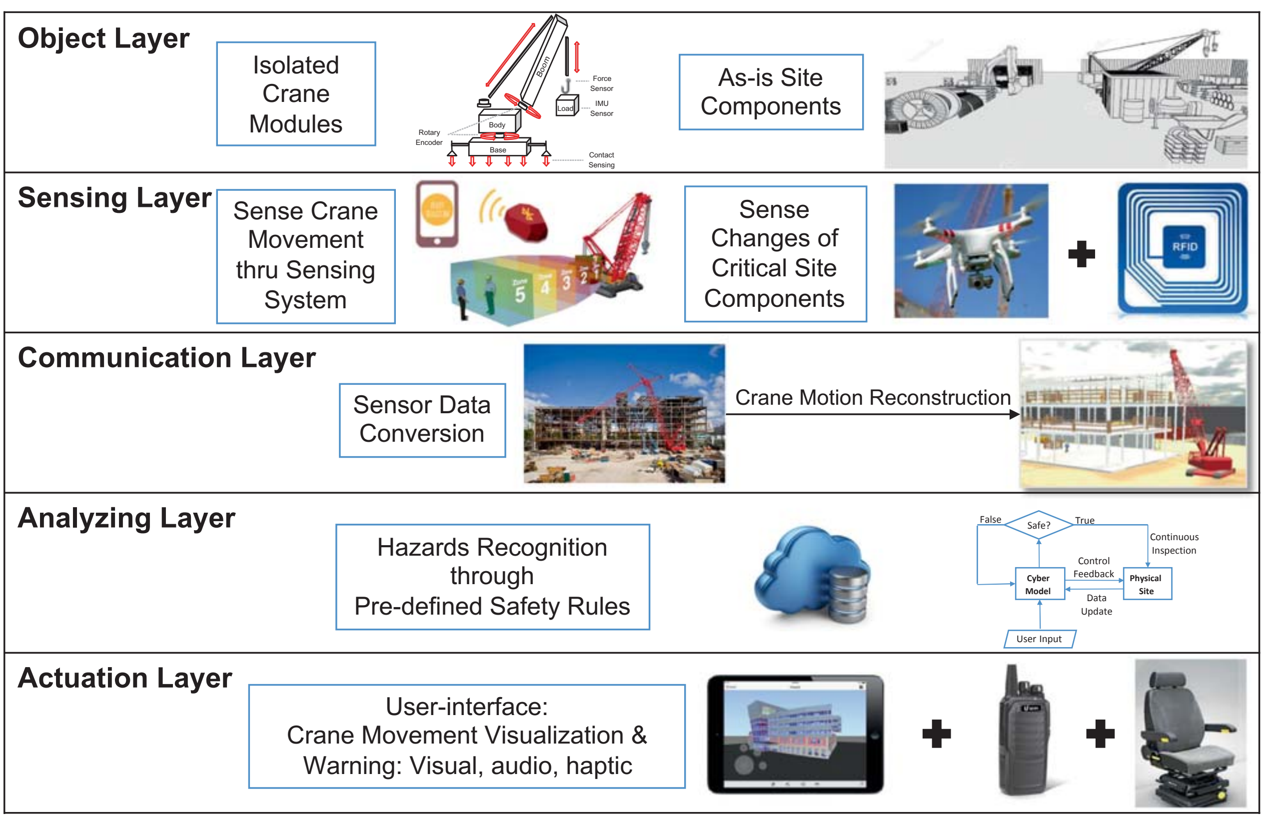


Fig. 78.2 System architecture for CPS-based real-time mobile crane operations

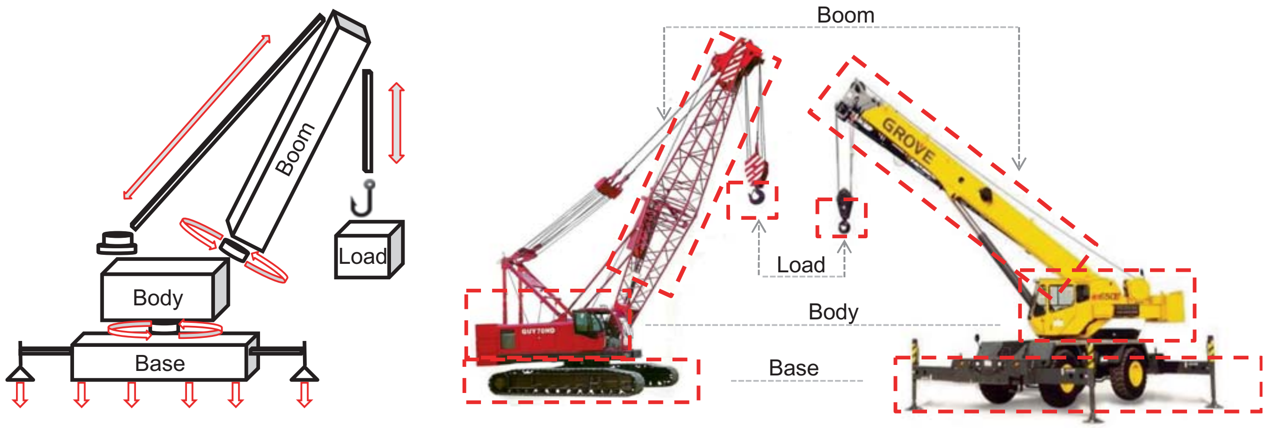


Fig. 78.3 Representation of isolated crane modules

Fig. 78.4 Locations for sensor installation

78.4.3 Communication Layer

The communication layer serves as a data processing unit and it is scripting-based. This unit processes the crane motion data and site environment data collected on the physical construction site through the sensing layer and converts it into software readable packets. These software readable packets are labeled as processed data. The processed data will reconstruct the crane motion and update the changes on site in the virtual site model, which will be discussed in the actuation layer later.

78.4.4 Analysis Layer

Once crane motions and the updates on site have been reconstructed, the processed data will be transferred from the communication layer to the analysis layer for the potential safety hazards to be analyzed. The key steps of how potential safety hazards are identified under the analysis layer are summarized and shown in Fig. 78.5.

In order to identify potential hazards associated with mobile crane, corresponding accident records from Occupational Safety and Health Administration (OSHA)'s website were studied. Based on the information extracted from the database, five potential failure modes including struck by, electrocution, crane tip-over, falls, and failure of boom/cable were identified. After the definition of the potential failure modes, thresholds were set to avoid these potential hazards. Regulations from OSHA, manuals provided by crane manufacturers, and industry best practices were considered while defining the threshold for potential hazards. More details concerning how the potential failure modes were identified and how the safety thresholds were defined can be found in [22].

78.4.5 Actuation Layer

The Actuation Layer consists of the virtual model developed and the user interface which presents the virtual model. In this layer, the mobile crane movement, site environment, the identified hazards, and the warning triggered are visualized simultaneously on a real-time basis. Details concerning how the virtual model is built and how the user-interface is designed are discussed in the following sub-sections.

Virtual Model. Unity 3D was selected as the software environment for virtual site model development. It is a game engine that supports cross platform scripting and can be used to create an as-is site model. Unity 3D was selected in this study for its ability to support cross-platform scripting, 3D modelling and visualization. Other platforms with similar capability would also be practical. Scripts were added to each part of a mobile crane model (e.g. base, body, boom and load) to allow each part of the crane to move freely in the virtual model as they do in the physical world. The motion of the crane model is built to be manipulated through a keyboard initially and later to be updated through the sensory data collected from the physical interface. A baseline construction site model is constructed and updated through the sensory data collected as well. Figure 78.6 shows a screenshot of the virtual site model. Scripts were pre-developed and embedded with the crane model as well as corresponding site components to account for all the five potential failure modes. Warning messages are triggered and shown once any potential hazards are detected based on the safety rules defined in the analyzing layer.

User Interface (UI). The user interface presented in Fig. 78.7 consists of three views: an isometric view shown on the left, a top view on top right and an operator's view on bottom right. The UI shows the re-constructed lifting scene and any warnings triggered in real-time. The detection of potential collision hazard is shown here as an example. Warning messages are triggered and the site components which are subject to the collision hazard are highlighted in red. The UI is proposed to be presented to the crane operator through a tablet PC installed in the operating cab. Workers on site are equipped with a mobile device which provides sound and vibration alerts upon breaching a hazardous area pre-defined with respect to the mobile crane.

78.5 Conclusions

This paper presented a CPS approach for the planning and monitoring of mobile crane operations on a real-time basis. With the aim of providing real-time safety assistance, a system architecture was presented and the key enabling technologies were discussed. The key conclusions that can be drawn from this study are presented as follows:

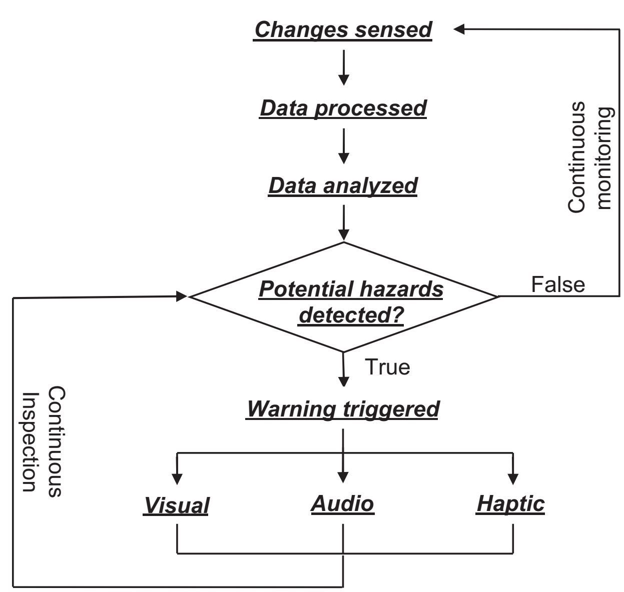


Fig. 78.5 Potential hazards identification [21]

Fig. 78.6 The simulated jobsite in unity 3D

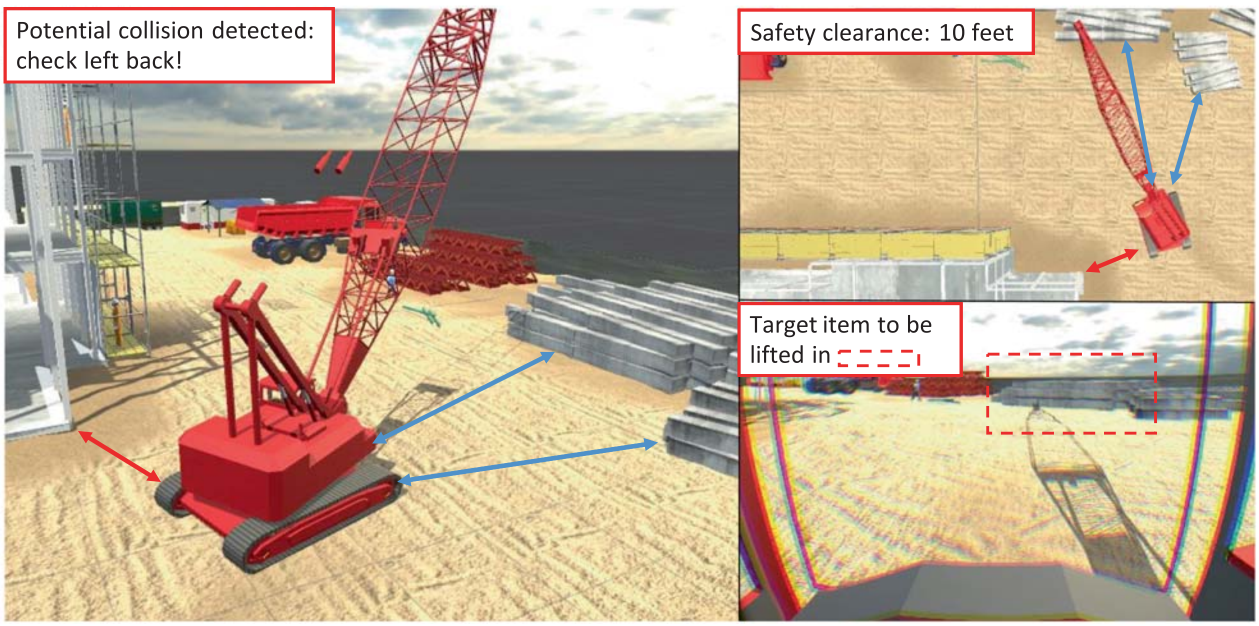


Fig. 78.7 User interface: crane movement visualization [21]

- The application of CPS on real-time mobile crane operations demonstrates how CPS plays an important role in enhancing bi-directional coordination between virtual models and their physical representations. The prototype system being developed is capable of tracking, monitoring the physical crane operations and giving real-time control feedback. It can be seen as an informative approach that provides information on the monitored state of the mobile crane and of the environment.
- The CPS-based approach enhances the communication and coordination between multiple parties. Project team members including the owner, crane manufacturer, project manager, workers and other personnel involved in the routine inspection can obtain information captured by the sensing system from the virtual model interface. It provides better opportunities for problem analysis, hazard avoidance, and collaborative working.
- With the capability of enhancing bi-directional coordination and information exchange, CPS offers advantages in effective planning, pro-active monitoring of crane operations, providing control feedback to both crane operator and workers on site thus ultimately reducing or avoiding mobile crane-related accidents.

However, there are several barriers standing in the way of utilizing a CPS-based approach for real-time mobile crane operations. Future work will focus on making estimation on mobile crane operating state, defining precise safety thresholds concerning each of the failure modes, and protecting the data collected from the sensing system from being tampered.

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