TECHNOLOGY

Peer-Reviewed

INTEGRATED & AUTOMATED SYSTEMS for Safe Construction Sites

By Jun Wang and Saiedeh Razavi

CONSTRUCTION IS AMONG THE MOST HAZARDOUS INDUSTRIES due to its unique nature such as dynamics and complexity (Awolusi, Song & Marks, 2017). According to U.S. Bureau of Labor Statistics (BLS, 2017) data, construction had the highest number of fatal work injuries among all investigated industry sectors (e.g., transportation, manufacturing, agriculture) for years 2012 to 2016.

Construction Safety & Risk Factors

Workplace fatalities have a tremendous impact on families, workplaces and communities. To prevent construction site incidents, researchers have made extensive efforts to identify root causes and contributory factors of construction incidents. Several categories of causes/factors of incidents have been obtained and summarized, including unsafe equipment, job site conditions, human factors and originating influences (e.g., construction design, management, safety education and training) (Gibb, Lingard, Behm, et al., 2014). Accordingly, countermeasures can be implemented to control the identified factors to avoid undesirable consequences in construction. Moreover, technologies play an important role in the process of controlling risk factors and offer new ways to keep workers safe in smart construction environments (Cheng & Teizer, 2013).

Of note, among the identified causes/factors, unsafe worker behaviors are considered the most significant contributing factor to occupational incidents in construction (more than 75% of construction injuries) (Tixier, Hallowell, Albert, et al., 2014). A major challenge is worker compliance with safe behaviors and safety procedures (Jitwasinkul, Hadikusumo & Memon, 2016). For example, something as simple as jumping a few feet to a lower level versus using stairs could lead to injury. Thus, having solutions to monitor worker behaviors and providing insight to timely correct unsafe behaviors can help to promote a safety culture across job sites and help workers take ownership of that culture (Blair, 2013; Seo, Han, Lee, et al., 2015). Extensive studies focusing on worker behaviors have been conducted to provide insight for construction safety enhancement, such as modeling construction worker behaviors (Ben-Alon & Sacks, 2017) and using various technologies such as wearable sensors and computer vision (Han & Lee, 2013). Despite the importance of investigating worker behaviors for safety management, modeling of worker behaviors is challenging due to the complex physiological, psychological and behavioral aspects of human beings (Munir, Stankovic, Liang, et al., 2013).

Existing studies mainly emphasize one specific aspect of safety enhancement, such as monitoring risk factors or identifying worker behaviors. However, to effectively prevent safety hazards in smart construction environments, a systematic and automated method is needed that integrates not only the noted aspects but also decision-making and timely actuations and feedback for preventive actions into one system. Considering the main causes/factors of incidents, the job site dynamics, and the human-related impacts and interactions in the process of safety monitoring and hazard prevention can help eliminate worker errors and prevent incidents through more reliable decision-making. The outcomes of existing studies provide valuable insight into developing such systematic and automated systems.

KEY TAKEAWAYS

- **Construction leads all industries in total worker fatal injuries in the U.S. Unsafe human behavior is considered a significant contributing factor to occupational incidents in construction.**
- **Technologies enable various innovative applications to enhance construction safety in a smart manner. Human-in-the-loop cyber-physical systems (HiLCPS), which are integrated and automated systems, are introduced to construction to improve situational awareness and proactively prevent incidents.**
- **Struck-by-equipment hazard is one of the leading causes of fatal injuries. This article presents a preliminary implementation of a prototype of HiLCPS for struck-by-equipment hazard in a controlled environment, aiming to contribute to the development of HiLCPS for real job sites. Full development and implementation of HiLCPS in construction is the continuation of this study.**
- **Accordingly, the authors identify three primary challenges associated with HiLCPS implementations: 1) seamless integration of the three domains of HiLCPS; 2) understanding and modeling of human behaviors and validation of human behavior-involved systems; and 3) development of reliable performance evaluation metrics.**

NICOLASMCCOMBER/E+/GETTY IMAGES

Human-in-the-Loop Cyber-Physical Systems

The main step to achieve automation and integration for safer job sites is providing the means to integrate all the aforementioned aspects involved in construction and technologies. Cyber-physical systems (CPS), a term referring to a new generation of systems, are coengineered interacting networks of physical and computational components. CPS are the integration of computation, networking and physical processes, and have been proposed and offered as an effective solution to meet the requirements for integration and automation (Esfahan, Du, Anumba, et al., 2017; Yuan, Anumba & Parfitt, 2016). The CPS approach is expected to bring advances in a wide range of fields including healthcare, emergency response, traffic flow management and construction, as well as in many other areas just being envisioned.

For example, load cells, switch sensors, an accelerometer and a displacement sensor were used to acquire data of a scaffold system in an experimental environment, a virtual model of the scaffold system was developed, an Android mobile app was developed for human-machine interaction and, accordingly, the app was automatically activated with alarms if a risk of scaffold failure was identified (Yuan, Anumba & Parfitt, 2016). Using CPS allows dynamics and changes in the physical world to be captured and reflected in the cyber world; also, changes and decisions in the cyber world can be communicated to sensors or actuators in the physical world for further actions. This bidirectional communication and coordination between physical and cyber worlds enable dynamic situations on construction sites to be continuously and timely monitored and analyzed, and potential hazards to be proactively identified and prevented through decision-making.

As noted, human-related factors play an essential role in the occurrence of construction incidents. Therefore, integrating human factors as a part of a CPS instead of placing them outside the system aids fully monitoring safety risk factors and achieving high integration and automation. However, such integrated, automated and comprehensive systems have not been investigated for construction safety. To reinforce CPS considering human factors, human-in-the-loop cyber-physical systems (HiLCPS) have been proposed (i.e., CPS operate in concert with humans). In HiLCPS, which are a category of CPS, humans are in the middle of the feedback loop between the cyber and the physical worlds of the system (Cuckov, Rudd & Daly, 2017). A human, a cyber world and a physical world compose a basic HiLCPS (Schirner, Erdogmus, Chowdhury, et al., 2013). HiLCPS either operate on humans or are built to augment humans' interactions with physical environments (Cuckov, Rudd & Daly). Thus, modeling construction safety problems as HiLCPS is a promising approach to comprehensively investigating safety hazards with causal factors and to improving situational awareness of workers.

Studies have explored applications of HiLCPS in multiple fields, such as healthcare for functionally locked-in individuals, automobile systems and energy management (Munir, Stankovic, Liang, et al., 2013). For example, HiLCPS are expected to facilitate functionally locked-in individuals to build interactions with the cyber-physical environment and restore fundamental autonomy (e.g., self-feeding, mobility, communication) in their daily life to contribute to a sense of self-fulfillment and a productive life (Schirner, Erdogmus, Chowdhury, et al., 2013). These outcomes shed light on further investigation and development of HiLCPS for safety management in the smart construction context. In summary, the HiLCPS approach offers benefits in many aspects including: 1) integration of cloud and sensor networks for timely observation, analysis and control; 2) monitoring and measurement of the situational awareness of humans for decision-making; and 3) fast response time to the early detected failures (Bhrugubanda, 2015).

Objectives

As noted, the primary objective of this study is to recommend applying HiLCPS in construction for safer sites. The HiLCPS aims to fully reflect aspects associated with safety hazards and to proactively reduce human errors and avoid incidents through enhanced situational awareness and decision-making. This article aims to achieve the following objectives:

- build the framework of HiLCPS with a high level of integration and automation for safer construction sites;
- define the scope and contents of the cyber world and the physical world, respectively;
- define the roles of humans in the framework.

Finally, the article reports a piece of sample work that contributes to realizing the HiLCPS for situational awareness enhancement by taking struck-by-equipment hazard as an example.

HiLCPS Framework for Construction Safety Enhancement

Figure 1 presents the HiLCPS framework. The following sections detail the three major components: cyber world, physical world and human interactions with them. The HiLCPS framework fully considers the interactions among human, physical world and cyber world, and achieves high automation and integration. HiLCPS are inherently complex systems, as human behaviors and decision-making are difficult to model, particularly with the inherent complexities of job sites and their high level of dynamics and uncertainty.

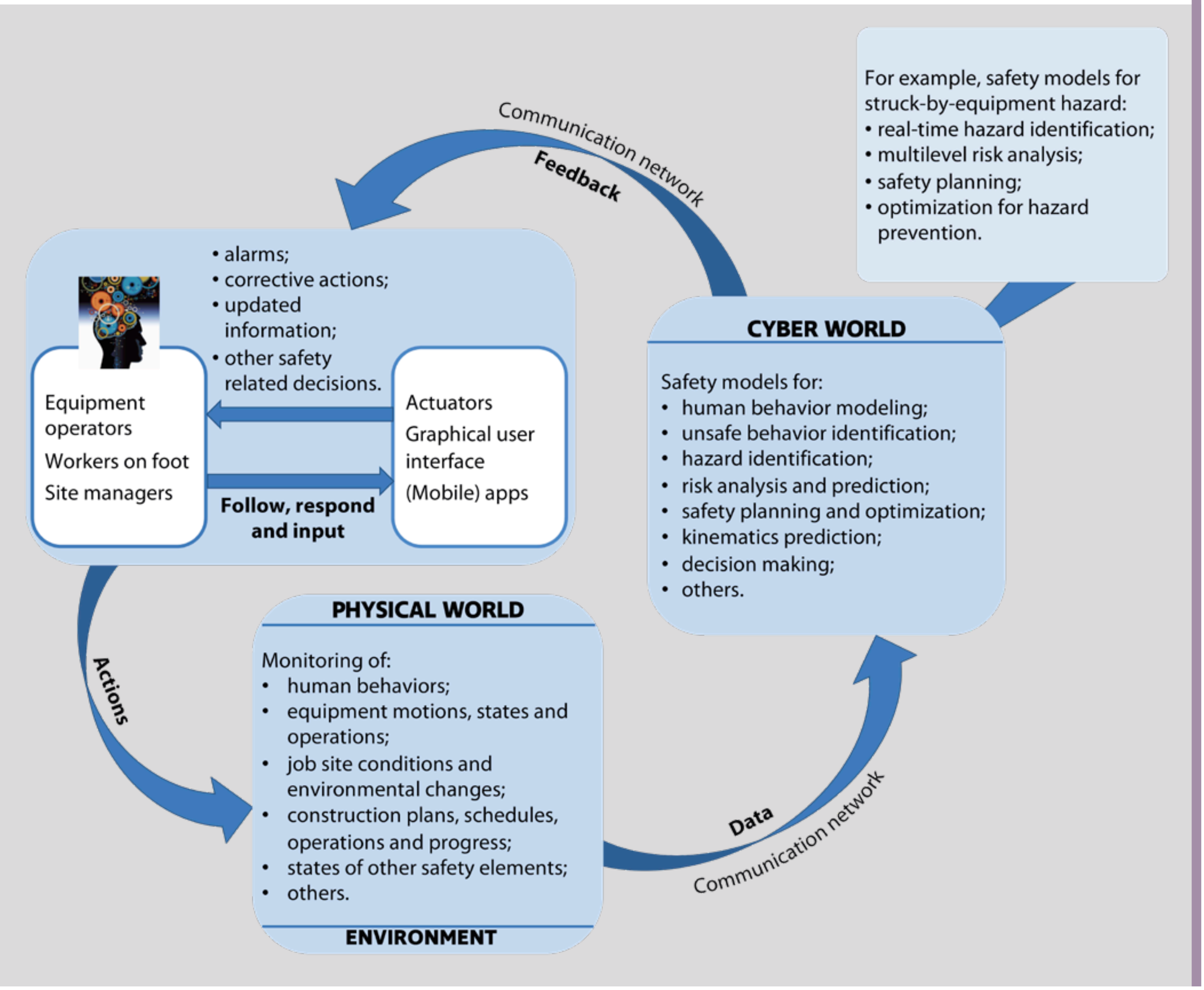
Physical World

Various technologies are used on sites and entities to track and collect data on aspects associated with safety hazards from the physical environment. These aspects include: 1) worker behaviors; 2) equipment motions, states and operations; 3) job site conditions and environmental changes; 4) construction plans, schedules, operations and progress; and 5) states of other safety elements (e.g., temporal structures on sites). For example, image-based technologies and body-sensor networks can be used to monitor workers' behaviors. The collected data reflecting the physical world are transferred via the communication network to the cyber world for processing. It should be noted that construction entities' motions are directly monitored in the physical world of HiLCPS, which is one representative case of HiLCPS (i.e., HiLCPS operate on humans) (Cuckov, Rudd & Daly, 2017).

Cyber World

To timely identify workers' unsafe behaviors and proactively prevent hazards, various safety-related models are embedded in the cyber world to analyze the data collected from the physical world. The embedded models include: 1) human behavior modeling models; 2) unsafe human behavior identification models; 3) hazard (e.g., fall, struck-by, electrocution) identification models; 4) safety risk analysis and prediction models; 5) safety planning and optimization models; 6) kinematics prediction models; and 7) decision models. Combined with the data analysis models, virtual models dynamically reflecting the physical world also can be developed. In Figure 1, taking struck-by-equipment hazard as an example, four categories of models (i.e., real-time hazard identification, multi-level risk analysis, safety planning, optimization for hazard prevention) suggested for

FIGURE 1
FRAMEWORK OF HiLCPS FOR SAFER CONSTRUCTION SITES



identifying and preventing struck-by-equipment hazards integrated into the cyber world are also presented.

Human Interactions With Physical World

Even in environments where systems are highly automated, humans play some role. Humans interact with the physical world and the interactions are augmented through HiLCPS, which is the other representative case of HiLCPS (Cuckov, Rudd & Daly, 2017; Schirner, Erdogmus, Chowdhury, et al., 2013). Decisions and instructions obtained from the cyber world are transferred to humans (e.g., equipment operators, workers on foot, site managers) through triggering actuators or presenting updated information (e.g., commands, instructions) on graphical user interfaces. Humans receive the updated information and, accordingly, apply actions to respond. The taken actions will directly affect the physical world (e.g., modify crane lift paths). As a result, the updated physical world is continuously monitored and data are collected and transmitted to the cyber world, repeating the loop of HiLCPS.

A Prototype of HiLCPS: Struck-by-Equipment Hazard Identification

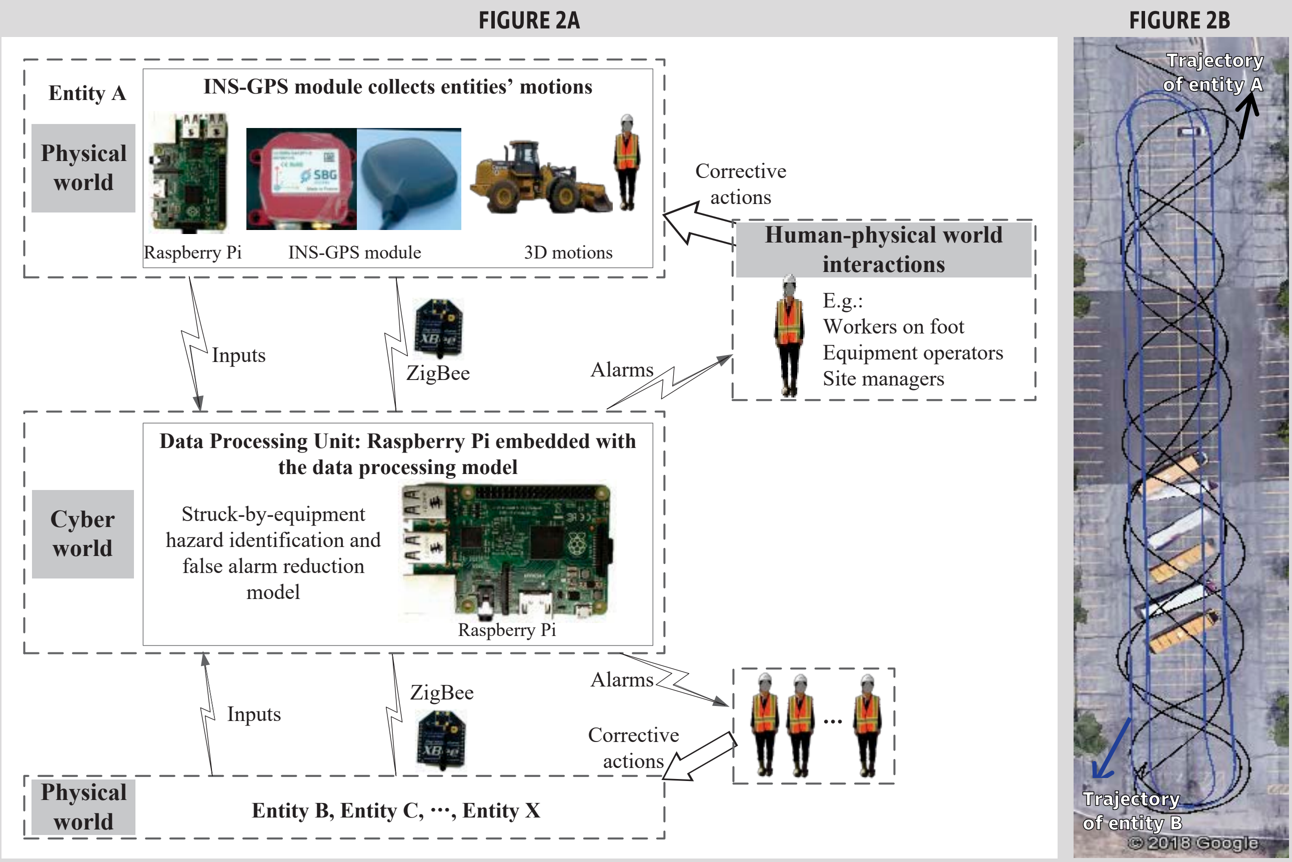
In construction, struck-by-equipment hazard (i.e., workers on foot struck by equipment or equipment struck by equipment) is one of the leading causes of fatal injuries. However, a major limitation of existing proximity-detection methods is the frequent generation of false alarms (Wang & Razavi, 2016). False alarms will cause interruptions to work and reduce productivity. Participants would ignore alarms and even disable alarm systems if false alarms are frequently generated. Therefore, a sample representation of HiLCPS focusing on struck-by-equipment hazard identification with reduced false alarms is presented, which contributes to the full development of HiLCPS for safer job sites in the next step of this study.

Overview of the Prototype

HiLCPS provide a fast, effective way for proactive and timely struck-by-equipment hazard prevention. In the physical world, motions (position, velocity and orientation) of workers on foot and equipment are monitored, collected and transmitted to the cyber world. The cyber world includes a model to process the received data for struck-by-equipment hazard identification. The included model can not only identify struck-by-equipment hazards but also reduce the generation of false alarms (see Wang & Razavi, 2016, for more details about the included model for false alarm reduction). The model is used and presented here to illustrate the cyber world of HiLCPS for construction safety enhancement. Instructions, decisions and updated information are timely communicated to site workers (e.g., workers on foot, equipment operators, managers) so that they can implement corrective actions accordingly (i.e., interactions between site workers and physical world are enhanced).

FIGURE 2

FRAMEWORK OF INTEGRATED INS-GPS-RASPBERRY PI SYSTEM & EXAMPLE TRAJECTORIES



Note. Figure 2a adapted from "An Integrated INS-GPS-Raspberry Pi System Using the Time-Sphere Model for Real-Time Identification of Struck-by-Equipment Hazard," by J. Wang, S. Du & S. Razavi, *Proceedings of the 33rd International Symposium on Automation and Robotics in Construction (ISARC)*, 2016. Figure 2b image ©2018 Google. Used with permission.

Preliminary Implementation of the Prototype

A preliminary implementation of a sample representation of HiLCPS for struck-by-equipment hazard is described. A developed system (Wang, Du & Razavi, 2016) integrating inertial navigation system (INS), GPS, Raspberry Pi, ZigBee, and the hazard identification and false alarm reduction model is used and described here, with the conducted controlled field experiment. Raspberry Pi is a low cost, credit-card sized, low-power computer with the ability to interact with the outside world. It is a flexible machine that has been used in a wide array of digital maker projects. Sensing and controlling of the physical world using computer programs can be run on a Raspberry Pi. The functions of Raspberry Pi in the INS-GPS-Raspberry Pi system are described here. The adopted INS is a navigation aid that integrates accelerometers, gyroscopes and magnetometers to get a moving object's position, orientation and velocity over time. Note that the INS-GPS-Raspberry Pi system is only a preliminary and exploratory work on HiLCPS to enhance construction safety. The framework of the integrated system is shown in Figure 2a and described as follows.

•Cyber world: The model noted (Wang & Razavi, 2016) is embedded in a Raspberry Pi, which is the central data processing unit to identify struck-by-equipment hazards and reduce false alarms. Human reaction and execution time are also considered in the embedded model for decision-making.

•Physical world: The controlled field experiment was conducted in a parking lot. A GPS-aided INS was used to collect entities' motions (position, velocity and orientation). The GPS-aided INS was embedded in a Raspberry Pi and the collected data were wirelessly sent to the cyber world using ZigBee (the wireless language to connect devices). Different scenarios were designed and conducted in the experiment and entities' motion trajectories were collected. For example, two collected trajectories uploaded to Google Earth are shown in Figure 2b.

•Interactions between human and physical world: LED lights (actuators) were embedded in each Raspberry Pi. If a hazardous proximity was identified, lights were triggered and flashing to alarm involved workers. Consequently, corrective actions were applied by workers to change entities' motions to avoid contact collisions. In this experiment, the driver braked without changing moving directions when an alarm was received. At the same time, entities' updated motions were tracked and sent to the cyber world for the analysis of another loop. In the next step of this work, other means such as display screen in equipment, automatic maneuver system, and behavior modification system can be explored and developed to assist workers and further enhance the interactions between construction workers and physical world.

The conducted experiment demonstrated the effectiveness of the model in identifying struck-by-equipment hazards with reduced false alarms and showed the promise of the system for real-world deployments. Entities' motions were tracked and monitored, and human interactions with the physical world were enhanced to prevent hazards. In addition to the hazard identification model, more safety models can be included in the cyber world to further eradicate and minimize safety risks.

Continuous and full development of the HiLCPS prototype for safety implementations on real construction sites is the next step of the work presented in this article.

Challenges of Applying HiLCPS for Construction Safety

HiLCPS present great promise to improve construction safety in a smart manner but also involve various challenges. The authors identify three major challenges:

•Seamless integration of the three HiLCPS domains (i.e., cyber, physical and human-related aspects) is essential for the effectiveness of HiLCPS in the real world and the key for its supreme advantages compared to other safety applications. However, challenges arise when expertise across domains is integrated into one system.

•Human is an essential component of HiLCPS for enhancing construction safety. Worker behaviors are monitored and analyzed for safety analysis; construction workers and managers must respond to alarms and apply corrective or notified actions to proactively prevent hazards. Understanding and accurately modeling human behaviors enables more effective development and implementation of HiLCPS in construction. However, modeling human behaviors is extremely challenging due to the complex physiological, psychological and behavioral aspects of humans. As a result, validation of human-behavior-involved systems is also challenging.

•As HiLCPS are composed of individual high-complexity systems, development of reliable performance evaluation metrics is another challenge; particularly, scalability and robustness are two principal aspects that must be considered in the performance evaluation. Accordingly, new optimization strategies for further development of HiLCPS can be investigated.

Also note that the widespread deployment of HiLCPS and realization of their full benefits in construction are long-term goals that require progress in multiple perspectives such as cybersecurity, software and hardware technologies, and policy. For example, the research on CPS software technology is still in the infancy stage, and mature software architecture is not available yet (Liu, Peng, Wang, et al., 2017). The achievement of the goals must simultaneously embrace all levels of the CPS/HiLCPS architecture, from the physical world and its associated sensors and actuators, through computation, networking and control, to the overall user functionality.

Conclusion

A systematic and automated system that integrates safety risk factors monitoring, safety analysis models, bidirectional communication and augmented human-system interactions is needed to reduce human errors and enhance decision-making for construction safety improvement. Therefore, the concept of HiLCPS is applied to construction for safety improvement. This article outlines the cyber and physical worlds and the interactions between human and the physical world to achieve integration and automation for situational awareness enhancement. A piece of preliminary work is presented to illustrate the HiLCPS framework for safer sites. The HiLCPS framework can be applied to different safety hazards and situations (e.g., potential hazards caused by workers' unsafe behaviors) on construction sites, providing an automated and integrated solution to develop safer construction job sites. **PSJ**

References

Awolusi, I., Song, S. & Marks, E. (2017, October). Forklift safety: Sensing the dangers with technology. *Professional Safety, 62*(10), 36-39.

Ben-Alon, L. & Sacks, R. (2017). Simulating the behavior of trade crews in construction using agents and building information modeling. *Automation in Construction, 74*, 12-27.

Bhrugubanda, M. (2015). A review on applications of cyber physical systems. *International Journal of Innovative Science, Engineering and Technology, 2*(6), 728-730.

Blair, E.H. (2013, November). Building safety culture: Three practical strategies. *Professional Safety, 58*(11), 59-65.

Cheng, T. & Teizer, J. (2013). Real-time resource location data collection and visualization technology for construction safety and activity monitoring applications. *Automation in Construction, 34*, 3-15.

Cuckov, F., Rudd, G. & Daly, L. (2017). Framework for model-based design and verification of human-in-the-loop cyber-physical systems. *Proceedings of the 10th IEEE International Conference on Software Testing, Verification and Validation Workshops (ICSTW)* (pp. 401-402).

Esfahan, N.R., Du, S., Anumba, C., et al. (2017). Smart tracking of highway construction projects. *Proceedings of the ASCE International Workshop on Computing in Civil Engineering (IWCCE)* (pp. 187-195).

Gibb, A., Lingard, H., Behm, M., et al. (2014). Construction accident causality: Learning from different countries and differing consequences. *Construction Management and Economics, 32*(5), 446-459.

Han, S. & Lee, S. (2013). A vision-based motion capture and recognition framework for behavior-based safety management. *Automation in Construction, 35*, 131-141.

Jitwasinkul, B., Hadikusumo, B.H.W. & Memon, A.Q. (2016). A Bayesian Belief Network model of organizational factors for improving safe work behaviors in Thai construction industry. *Safety Science, 82*, 264-273.

Liu, Y., Peng, Y., Wang, B., et al. (2017). Review on cyber-physical systems. *IEEE/CAA Journal of Automatica Sinica, 4*(1), 27-40.

Munir, S., Stankovic, J.A., Liang, C.J.M., et al. (2013). Cyber physical system challenges for human-in-the-loop control. *Proceedings of the 8th International Workshop on Feedback Computing, San Jose, CA*.

Schirner, G., Erdogmus, D., Chowdhury, K., et al. (2013). The future of human-in-the-loop cyber-physical systems. *Computer, 46*(1), 36-45.

Seo, J., Han, S., Lee, S., et al. (2015). Computer vision techniques for construction safety and health monitoring. *Advanced Engineering Informatics, 29*(2), 239-251.

Tixier, A.J.-P., Hallowell, M.R., Albert, A., et al. (2014). Psychological antecedents of risk-taking behavior in construction. *Journal of Construction Engineering and Management, 140*(11).

U.S. Bureau of Labor Statistics (BLS). (2017). Census of fatal occupational injuries, 2012-2016. Retrieved from www.bls.gov/iif/oshcfoi1.htm

Wang, J. & Razavi, S. (2016). Two 4-D models effective in reducing false alarms for struck-by-equipment hazard prevention. *Journal of Computing in Civil Engineering, 30*(6).

Wang, J., Du, S. & Razavi, S. (2016). An integrated INS-GPS-Raspberry Pi system using the time-sphere model for real-time identification of struck-by-equipment hazard. *Proceedings of the 33rd International Symposium on Automation and Robotics in Construction (ISARC)*.

Yuan, X., Anumba, C.J. & Parfitt, M.K. (2016). Cyber-physical systems for temporary structure monitoring. *Automation in Construction, 66*, 1-14.

Jun Wang, Ph.D., is an assistant professor in the Department of Civil and Environmental Engineering at Mississippi State University. Wang's research focuses include smart construction and systems, safety risk analysis, human factors in construction and resilient infrastructure systems. Wang holds a Ph.D. in Civil Engineering from McMaster University, Canada, and an M.Sc. and B.Sc. from Dalian University of Technology, China.

Saiedeh Razavi, Ph.D., is an associate professor in the Department of Civil Engineering at McMaster University, the director of McMaster Institute for Transportation and Logistics and the inaugural chair in heavy construction. Her multidisciplinary background includes leading national and international multidisciplinary team-based projects in sensing and data acquisition, sensor technologies, data analytics, data fusion and their applications in transportation, construction and other systems. Razavi holds a B.Sc. in Computer Engineering from Sharif University of Technology, an M.Sc. in Artificial Intelligence from Iran University of Science and Technology, and a Ph.D. in Civil Engineering from University of Waterloo.