INFORMATION TECHNOLOGY APPLICATIONS IN CONSTRUCTION SAFETY ASSURANCE

Mirosław J. SKIBNIEWSKI

Department of Civil and Environmental Engineering, University of Maryland, College Park, MD 20742, USA
Institute for Theoretical and Applied Informatics, Polish Academy of Sciences, 44-100 Gliwice, Poland

Abstract. Through analysis of articles published from 2006 to July 2014 this paper summarizes the topics of research and the institutions where research was conducted in the field of computer-based construction safety engineering management. One hundred and thirty-six articles published during this time focused on Information Technology (IT) applications in this field were selected for analysis. The underlying research topics and their related IT implementations are discussed, and research trends in allied specialties are identified.

Keywords: safety management, construction, building engineering, information technology, international research journal, research trends.

Introduction

Construction is one of the most dangerous industries, causing numerous casualties and property loss in every country around the world. Due to the improvement of production technology in construction, the ever expanding size and complexity of infrastructure projects, and increased expectations in regard to safety performance safety management has become a major challenge to the industry at large. Advances in safety sciences and information technology present an unprecedented opportunity to positively impact the safety performance in construction. There is a compelling need for further innovation to address challenges towards improving the safety performance of the construction industry globally (Kamardeen 2013).

Information technology-based field data acquisition equipment and tools are instrumental in achieving an ever increasing ability to store, retrieve, transmit and manipulate data and information during the conduct of construction projects. Precise and real-time control over workers, equipment, materials, construction methods and work environment are need for safety risk prevention and emergency response. Research on perceived risk based on sensors is conducted to monitor and analyze the safety status on construction sites to prevent workers from being exposed to hazards (Cheng, Teizer 2014; Nadar *et al.* 2013). Robotics and remotely controlled manipulators have been invented and are being improved for high-safety-risk construction activities (Jung *et al.* 2013; Han *et al.* 2006). Information systems have been widely discussed for managing massive multi-source heterogeneous data generated during construction and occupational hazard on site was assessed, so that consistent and timely data can be shared between project participants for effective safety collaborations (Lee *et al.* 2014; Dėjus, Antuchevičienė 2013).

Through the investigation of over one hundred and thirty articles from Web of Science™ and Scopus™ posted in the last 8 years, this paper presents a general review of research related to IT implementations in construction safety. All statistics in this paper are derived from these articles.

1. Publication statistics

From 2006 to July 2014, one hundred and thirty-six articles on Information Technologies for construction safety management were published or were available on the Web of Science™ and in Scopus™. A subset of the compilation presented herein focused on papers from *Automation in Construction*, an international research journal (Skibniewski 2014). As shown in Figure 1, the increasing number of publications after 2008 indicates a growing concern for construction safety management and the growing number of proposed implementations of Information Technologies in this field. Research on construction site monitoring and worker/equipment safety has been carried out with the use of Radio Frequency Identification (RFID) technologies, Ultra-wide Band (UwB) and Wireless Networks (WN), Building Information Modeling (BIM) applications, and others.

As shown in Table 1, the one hundred and thirty-six analyzed articles can be categorized into three major themes as follows: 1) Sensors and sensor-based systems for construction safety; 2) Robotics and manipulators for construction safety; 3) Information analysis and management along with reporting systems for construction safety.

Corresponding author: Mirosław J. Skibniewski
E-mail: mirek@umd.edu

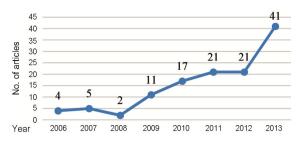Taylor & Francis
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Fig. 1. Publications on IT in construction safety management

The top ten countries from which the largest number of published articles originated in the past 8 years are shown in Table 2. China, USA and Korea contributed 106 (78%) of the articles. Considering the massive construction volume in China, a large volume of research on both worker and equipment safety has been reported

Table 1. Classification of articles on IT in construction safety published

Paper Classification	No. of Articles	Proportion to all Articles on IT for Construction Safety (January 2006 – July 2014)
Sensors and sensor-based systems for construction safety	37	27.21%
Robotics and manipulators for construction safety	18	13.24%
Information analysis and management and reporting systems for construction safety	81	59.56%
Total	136	100.00%

Table 2. Countries of origin of articles on IT in construction safety (per origin of the corresponding author)

Country	No. of Articles	Proportion to all Articles on IT for Construction Safety (January 2006 – July 2014)	Rank
Greater China (incl. PRC, Hong Kong, Taiwan RoC)	53	39%	1
USA	35	26%	2
South Korea	18	13%	3
Canada	5	4%	4
Lithuania	4	3%	5
Italy	3	2%	6
Japan	3	2%	6
Australia	2	1%	8
England	2	1%	8
Finland	2	1%	8
Germany	2	1%	8
Poland	2	1%	8
Spain	2	1%	8

involving the use of a variety of IT tools. Among other publications, researchers based in the USA and South Korea published five articles on their joint robotic and information systems research aimed at achieving improved construction safety performance.

Most active research institutions in IT for construction safety represented by corresponding authors are provided in Table 3 and statistics on corresponding authors in Table 4.

Table 3. Most active research institutions in IT for Construction Safety represented by corresponding authors

Rank	Country	Research institution	No. of articles
1	China	(1) Huazhong University of Science & Technology	17
		(2) Tsinghua University	3
		(2) Southeast University	3
		(2) Wuhan University of Technology	3
2	USA	(1) Georgia Institute of Technology	14
		(2) University of Michigan	3
		(3) California State University	2
3	South Korea	(1) Korea University	3
		(1) Yonsei University	3
		(3) Gyeongsang National University	2

2. Types of research on IT-based construction safety management

2.1. Sensors and sensor-based systems for safety

Although construction professionals have made efforts to improve safety training, site supervision and design for safety, the safety performance in construction is still unsatisfactory, mainly due to human errors and lack of situational awareness during construction activities. Recent advances in sensing and computing technologies offer a solution for improving safety performance by providing rich information about location and worker safety (Marks, Teizer 2013).
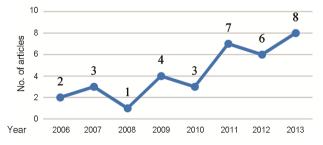

Fig. 2. Articles published between 2006 and 2013 on sensors and sensor-based systems for construction safety

There have been thirty-seven articles published on sensors and sensor-based system in the past 8 years, as shown in Table 5 and Figure 2. Twenty-four research institutions from seven countries and three continents have been active in research on this topic. Almost one third of these articles are focused on the use of RFID

Table 4. Corresponding authors of papers on IT-based construction safety management

Corresponding author	Research institution	No. of articles by Corresponding Author	Proportion to all articles on IT for Construction Safety (January 2006 – July 2014)	Rank
Jochen Teizer	RAPIDS Laboratory (formerly at Georgia Institute of Technology)	13	9%	1
Lieyun Ding	Huazhong University of Science and Technology	5	4%	2
Alessandro Carbonari	Università Politecnica delle Marche	3	2%	3
Ruta Simanaviciene	Vilnius Gediminas Technical University	3	2%	3
Xianguo Wu	Huazhong University of Science and Technology	3	2%	3
Cheng Zhou	Huazhong University of Science and Technology	2	1%	6
Daehie Hong	Korea University	2	1%	6
Farnaz Sadeghpour	University of Calgary	2	1%	6
Ghang Lee	Yonsei University	2	1%	6
Jianping Zhang	Tsinghua University	2	1%	6
LeenSeok Kang	Gyeongsang National University	2	1%	6
M. Kasirossafar	California State University	2	1%	6
SangHyun Lee	University of Michigan	2	1%	6
Soungho Chae	Kajima Technical Research Institute	2	1%	6
Ying Ye	Beijing Municipal Engineering Research Institute	2	1%	6
Zhipeng Zhou	Southeast University	2	1%	6

Table 5. Corresponding authors of papers on sensors and sensor-based systems for construction safety management

Research institution	Total no. of articles from institution	Corresponding author	No. of articles by Corresponding Author	Proportion to sensor and sensor-based systems articles on IT for Construction Safety (January 2006 – July 2014)	Rank
Georgia Institute of Technology	9	Jochen Teizer	8	24%	1
		Tao Cheng	1		
Università Politecnica delle Marche	3	Alessandro Carbonari	3	8%	2
Kajima Technical Research Institute	2	Soungho Chae	2	5%	3
University of Calgary	2	Farnaz Sadeghpour	2	5%	3
University of Southern California	2	Burcin Becerik-Gerber	1	5%	3
		Gulben Calis	1		
ACCIONA Infraestructuras	1	Sara Prior Peinado	1	3%	6
American University of Beirut	1	Hiam Khoury	1	3%	6
Chinese Academy of Sciences	1	Jianguo Yang	1	3%	6
Chinese Academy of Surveying and Mapping	1	Yan Lv	1	3%	6
Chung-Ang University	1	Hyeon-Jin Kim	1	3%	6
City University of Hong Kong	1	Ivan W.H. Fung	1	3%	6
Concordia University	1	Saiedeh Nawabzadi Razavi	1	3%	6
Environmental Management College of China	1	Hong Fen Wang	1	3%	6
Kyonggi University	1	Gwanghee Kim	1	3%	6

Continued Table 5

Research institution	Total no. of articles from institution	Corresponding author	No. of articles by Corresponding Author	Proportion to sensor and sensor-based systems articles on IT for Construction Safety (January 2006 – July 2014)	Rank
Lamar University	1	Seokyon Hwang	1	3%	6
Southeast University	1	Weiwei Wu	1	3%	6
Sungkyunkwan University	1	Su Won Yoon	1	3%	6
The University of Texas at Austin	1	Sooyoung Choe	1	3%	6
University of Arkansas	1	Haiyan Xie	1	3%	6
University of Michigan	1	SangHyun Lee	1	3%	6
University of Nebraska	1	Yong Cho	1	3%	6
University of Texas at Austin	1	Fernanda Leite	1	3%	6
Xi'An University of Architecture and Technology	1	Lichen Gu	1	3%	6
Yonsei University	1	Ghang Lee	1	3%	6

(Calis *et al.* 2011; Chae 2009; Chae, Yoshida 2010; Kelm *et al.* 2013; Lee *et al.* 2012b; Li *et al.* 2012b; Marks, Teizer 2013; Peinado *et al.* 2009; Razavi *et al.* 2012; Xie *et al.* 2011; Yoon *et al.* 2006), a type of automatic identification technology in which radio wave frequencies are used to capture and transmit data from a tag, or transponder.

2.1.1. RFID sensors

The major applications of RFID sensors are the developments of safety early warning systems that could inform workers of potential safety risks on site. As shown in Figure 3, with real-time visible and traceable information, equipment collision accidents can be prevented if workers-on-foot and equipment operators have been warned or alerted when one gets too close to the equipment (Chae, Yoshida 2010). Besides conflict zone detection and vertical construction resource tracking, a three-dimensional location-sensing algorithms have been developed to analyze the possible 3D locations of objects based on RFID sensor-generated information. However, the signal attenuation effect caused by the surrounding environment was not taken into consideration in these studies.
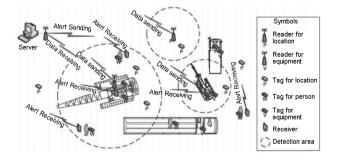

Fig. 3. Location of tags and divided excavation area (Chae, Yoshida 2010)

As ZigBee technology provides a reliable, low cost and easy to deploy wireless sensor network solution, researchers have explored the feasibility to use Zigbee RFID sensors networks to prevent workers from being struck by falling objects, and to track near-miss accidents by tracking the allocation of workers, equipment and materials (Wu *et al.* 2010). Although the field trial in a warehouse indicated the tracking signal would be weakened when emitters are obstructed, this problem can be overcome with a careful layout. Research on monitoring interference between teams at work can lead to the ability to alert project personnel of the occurrence of physical interference of work crews and to identifying and predicting problematic work conduct by workers (Naticchia *et al.* 2013). The RFID tags can be attached to safety gear such as Personal Protective Equipment (PPE) to support the compliance checking process (Kelm *et al.* 2013). In an event of non-compliance with safety-mandated behavior, recording of the presence of workers on-site and checking whether any member of a team accessed an unauthorized area where interference with other work teams could take place would be possible. Nonetheless, a number of remaining problems need to be solved before such systems can be implemented in industry practice. Besides the concerns for capturing real-time information of workers on site, automatic, real time zoning updates of construction sites for safety, and registering potential risks using RFID tags are still among the unresolved issues. Technical and financial challenges with RFID-enabled safety precaution systems need to be further explored.

2.1.2. Automated tracking based on ultra-wideband sensor

Emerging wireless remote sensing technologies offer significant potential to advance the management of construction processes by providing real-time access to the locations of workers, materials, and equipment. Depending on site constraints and on the scope of management

activities, past research has shown that predicting potential risk situations calls for real-time intelligent site monitoring and the ability to react when the level of risk increases. To date, the most promising tracking technology are RFID, Global Positioning System (GPS), Wireless Local Area Networks (WLAN), UwB and Indoor GPS, for their ability to cover a wide range of accuracy values and yard areas. UwB (Ultra-wide Band) is a radio-based technology that may be used at a very low energy level for short-range, high-bandwidth communications using a large portion of the radio spectrum. Unfortunately, little is known regarding the accuracy, reliability, and practical benefits of this emerging technology, effectively impeding widespread adoption. In face of that, efforts are made to evaluate the performance, including tracking accuracy, location error rates of a commercially available UWB systems for real-time, mobile resource location tracking in challenging construction environments (e.g. resource rich, spatially complex, cluttered with metallic objects causing interference). Sufficient accuracy for practical implementation was achieved in large open space construction environments (Cheng *et al.* 2011) (see Fig. 4).
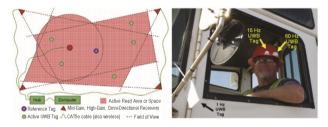

Fig. 4. Triangulation of UwB tags using UwB receivers that overlap the coverage area/space inside a lay-down yard (Cheng *et al.* 2011)

For outdoor automated applications of dynamic tracking based on an UwB technology, a prototype system for proactive safety management and real-time signalling of potential overhead hazards was developed. The system was conceived to act without the need to tag workers and other resources. Distances are in fact measured through IR and ultrasonic sensors. Its results suggest further system enhancement geared towards use cases involving dynamically changing hazardous areas (Carbonari *et al.* 2011). By consistently tracking the real-time position of workers involved on construction sites, measures can be taken to prevent non-authorized access to dangerous zones (Giretti *et al.* 2009). A method for preventing equipment collision by helping equipment operators improve their situational awareness while operating equipment on site was also reported. Although this study was only conducted at a laboratory scale, the reported research examined technical feasibility and expected benefits of integrating collision-prevention approaches with UWB technology for preventing equipment collisions (Hwang 2012).

For indoor scenarios, another study aimed at assessing performance of UwB tracking systems in a static mode under a set of conditions that can commonly occur on construction sites. The study measured the extent of the impact of variables that represent seven conditions that would have a negative impact on the accuracy of the location estimation data provided by UwB (Maalek, Sadeghpour 2013). The study reported an evaluation of the static and dynamic performance of a commercially-available UwB tracking system in free space and under realistic construction environment scenario. The results of these tests were in agreement with the manufacturer specifications for the UWB systems tested in outdoor environment (Saidi *et al.* 2011).

2.1.3. Other sensor-based research

For a construction equipment operator encountering blind spots, a navigation system that provides 3D information in real time about a building and its surroundings, and the position of the object being lifted have been developed using laser and encoder sensors (Lee *et al.* 2012a). Ultrasonic sensors are used to gradually obtain the accurate state of barriers, security judgment and Anti-Collision alarm through multi-sensor information fusion techniques (Li *et al.* 2012c). With positioning and personal ID sensors in the worker's hardhat, actual location of each worker is compared and verified with a database containing the tasks and processes being performed on site.

2.2. Robotics and manipulators for safety

The construction industry has been a challenging field for the application of robotic technologies. At the same time, the construction industry involves dangerous environmental characteristics which cause poor working conditions for construction laborers making it desirable to employ robots in the aid of, or instead of human workers (Skibniewski 1988). Replacing human labor with robotic systems has as the potential of increased quality, productivity and safety. Due to the complexity of research on robotics and manipulators, articles focused on this category of topics are relatively fewer than other categories analyzed in this paper, see Figure 5.
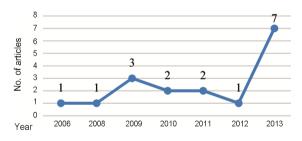

Fig. 5. Articles on robotics and manipulators for construction safety

2.2.1. Human–machine interaction for automated construction

Collaboration between a robot and a human worker during construction may be highly beneficial in achieving improved productivity and quality levels. In extreme project environments, construction robots may be the only equipment suitable for work performance, particularly in chemically or radioactively contaminated construction environments. For example, an automated

excavation system, incorporating the intelligence of a construction planner and a skilful operator, has been developed to generate an optimal excavation plan based on 3D models of the structure being constructed in a given work environment and of the excavator (Seo *et al.* 2011). Other studies have focused on automated systems for lifting heavy structural components, transportation and assembly aiming at precise control of the work being performed. To cope with the lack of skilled workforce and with increased levels of hazards for human workers, a Genetic Algorithm-based Repetitive Tasks Simulation (CARTS) model has been developed for planning steel erection in high-rise building construction. The results have shown the model's capacity and justified its application to generic types of robotic construction systems (Yoo *et al.* 2012). A method based on strength tests for protective structures for construction equipment to prevent roll-over has been presented (Karliński *et al.* 2013).

A robotic beam assembly (RBA) system was developed to execute a beam assembly task (Jung *et al.* 2013), see Figure 6. Another application in steel construction focuses on a robotic performance of steel beam assembly. The robotic steel beam assembly system consists of a robotic bolting device that performs the main function for the beam assembly work and a robotic transport mechanism that transports the robotic bolting device to target bolting positions around a building under construction (Chu *et al.* 2013). Through field tests of the prototype and its application to a building construction project, the study shows the potential to replace laborers with a robotic system for steel beam assembly during high-rise building construction. Other research on vertical transportation in lifting construction materials to elevated locations where the material is to be installed, as an alternative to traditional tower cranes, has also been reported in the form of a robotic tower-crane system. Additionally, the feasibility of laser-technology-based lift-path tracking for a robotic tower-crane has been examined. Instead of traveling only through pre-planned paths, the proposed robotic tower-crane has shown the feasibility under various jobsite conditions (Lee *et al.* 2009). Research activities on tower crane visibility and operational conditions were conducted as well (Cheng, Teizer 2014; Tam, Fung 2011; Zhang *et al.* 2013c).
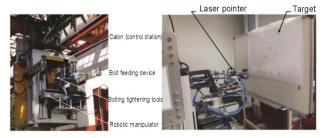

Fig. 6. The control devices in the cabin and experimental environment for the pointing task (Jung *et al.* 2013)

2.2.2. Evaluation of current robotics and manipulators

Pipe laying work involves the work of human laborers in trenches, one of the least safe construction tasks. Two papers published over the last decade discuss existing construction machinery for concrete pipe laying. One paper evaluates performance of the Hume Concrete Pipe Manipulator (HCPM) commissioned by the Korea Ministry of Construction and Transport. Based on the analysis of HCPM's overall work performance on a construction site, 65% in productivity improvement, and 33% in cost savings has been reported (Kim *et al.* 2009). Additionally, comparisons have been described between researches teams in Korea and in the US focused on installing large concrete pipe tele-robotically. Authors compare how the two research teams have solved some of the most unique technical problems in these operations, and present the lessons learned during the field tests without human personnel in the trench. Both prototypes reported improvements in productivity and unit cost (Kim, Elernold 2008).

Major institutions and corresponding authors on robotics and manipulators for construction safety management are provided in Table 6.

Based on the quantity of publications alone, it appears that Korea has had the most active research program in this field, as it has contributed 50% of all articles on robotics and manipulators for construction safety management. During the analyzed period a total of 16 research institutions from 8 countries and 4 continents have been active in this field.

2.3. Information analysis, management and reporting systems for safety

As shown in Figure 7, research papers related to BIM application to improving construction safety, laser scan status capture and early warning system were published in increasing numbers in 2013 due to the publication of a special issue based on expanded, updated and refereed papers presented at Australasian Conference on Innovative Technologies in Construction (ITC2012) in June 2012.
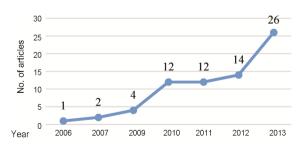

Fig. 7. Articles on information analysis and reporting systems for construction safety

As shown in Table 7, over 40 research institutions from 13 countries and 5 continents were involved in construction safety research focused on the implementation of IT tools. These institutions were based mostly in China and in the USA (Zhou *et al.* 2013b; Zhang *et al.* 2013b).

Table 6. Major institutions and corresponding authors on robotics and manipulators for construction safety management

Research institution	Total no. of articles from institution	Corresponding Author	No. of articles by Corresponding Author	Proportion to robotics and manipulators articles on IT for Construction Safety (Jan. 2006 – July 2014)	Rank
Korea University	2	Daehie Hong	1	11%	1
		Hunhee Cho	1		
Yonsei University	2	Ghang Lee	1	11%	1
		Hyoungkwan Kim	1		
Changchun University of Technology	1	Xinxing Tang	1	6%	3
Chongqing University	1	Nanqing Zhang	1	6%	3
Concordia University	1	Amin Hammad	1	6%	3
Georgia Institute of Technology	1	Jochen Teizer	1	6%	3
Hanyang University	1	Chang Soo Han	1	6%	3
Inha University	1	Young S. Kim	1	6%	3
Institute for Ferrous Metallurgy	1	Janusz Dobrzański	1	6%	3
Kinki Regional Development Bureau	1	Hiroshi Yamamoto	1	6%	3
Korea Institute of Construction Technology	1	Kyoon-Tai Kim	1	6%	3
Korea University	1	Daehie Hong	1	6%	3
Seoul National University of Science & Technology	1	Sung-Keun Kim	1	6%	3
Universidad de Malaga	1	JC Rubio-Romero	1	6%	3
University of Western Sydney	1	Vivian W. Y. Tam	1	6%	3
Wrocław University of Technology	1	Mariusz Ptak	1	6%	3

Table 7. Research institutions and corresponding authors on information analysis and reporting systems for construction safety management

Research institution	Total no. of articles from institution	Corresponding Author	No. of articles by Corresponding Author	Proportion to robotics and manipulators articles on IT for Construction Safety (Jan. 2006 – July 2014)	Rank
Huazhong University of Science & Technology	17	Lieyun Ding	5	21%	1
		Xianguo Wu	3		
		Cheng Zhou	2		
		Hanbin Luo	1		
		Ying Zhou	1		
		Ling Ma	1		
		Hongliang Yu	1		
		Fan Wang	1		
		Qingnian Yang	1		
		Guocheng Li	1		
Georgia Institute of Technology	4	Jochen Teizer	4	5%	2
Tsinghua University	3	Jianping Zhang	2	4%	3
		Zhenzhong Hu	1		
Vilnius Gediminas Technical University	3	Ruta Simanaviciene	3	4%	3
Wuhan University of Technology	3	Gaofeng Ren	1	4%	3
		Hao Wu	1		
		Qiankun Wang	1		

Continued Table 7

Research institution	Total no. of articles from institution	Corresponding Author	No. of articles by Corresponding Author	Proportion to robotics and manipulators articles on IT for Construction Safety (Jan. 2006 – July 2014)	Rank
Beijing Municipal Engineering Research Institute	2	Ying Ye	2	2%	6
Beijing University of Technology	2	Yanfeng Li	1	2%	6
		Wenxue Gao	1		
California State University	2	Mohammad Kasirossafar	1	2%	6
Chengdu University of Technology	2	Yuping Qing	1	2%	6
		Lubo Meng	1		
Gyeongsang National University	2	LeenSeok Kang	2	2%	6
Southeast University	2	Zhipeng Zhou	2	2%	6
University of Colorado	2	Matthew Hallowell	1	2%	6
		Behzad Esmaeili	1		
University of Michigan	2	SangHyun Lee	1	2%	6
		Sanat A. Talmaki	1		
Virginia Polytechnic Institute	2	Dong Zhao	1	2%	6
		Mani Golparvar-Fard	1		
VTT Technical Research Center	2	Kristiina Sulankivi	1	2%	6
		Markku Kiviniemi	1		
Anadolu University	1	Serkan Kivrak	1	1%	16
Arizona State University	1	Samuel T. Ariaratnam	1	1%	16
Bauhaus-Universität Weimar	1	Juergen Melzner	1	1%	16
Beijing Polytechnic College	1	Shenglin Wu	1	1%	16
Buchting Streit AG	1	Karl Schikora	1	1%	16

2.3.1. BIM-based spatial-schedule conflict analysis and structural safety

Schedule-workspace interference is generated when workspaces that share parallel schedules and are physically adjacent to one another exist simultaneously. When workspace interference is generated, securing work performance safety is difficult and constructability can deteriorate due to increased collision risk between resources. In view of this BIM was used for safety planning on site layout planning and visualization before construction (Kasirossafar, Shahbodaghlou 2013b; Kiviniemi *et al.* 2011; Sulankivi *et al.* 2009). For the construction phase of a project, a study related to situation awareness of equipment operators has been completed using Differential Global Positioning System (DGPS), wireless technologies. The researchers developed and implemented technologies for vehicle tracking and collision detection to sense their environment with the objective of increasing safety and improving productivity on construction sites. An active simulation system has been reported in 2014 using a genetic algorithm (GA) process for an alternative schedule that minimizes the level of interference in the schedule-workspace (Moon *et al.* 2014b). Based on new developments in BIM, four-dimensional (4D) technology,

time-dependent structural analysis and collision detection, a 4D structural information model was presented as a proposed solution to spatial-scheduling conflicts and safety hazards during construction (Zhang, Hu 2011).

Using a combination of augmented reality (AR), location tracking, and game technologies, Korean researchers proposed a framework for BIM-based safety management and visualization, and a rule-based checking system to include automated hazard identification and abatement during the construction planning phase (Zhang *et al.* 2013d).

2.3.2. Metro construction safety early warning systems

As meaningful improvement in safety performance in metro construction is difficult, time-consuming and unreliable due to the lack of safety performance information and of experienced safety managers. Safety management in large-scale projects requires understanding and addressing technical and managerial complexities involved in the design and implementation of these projects (Zhou *et al.* 2010).

In pre-construction phrase, estimations of safety risk level and distribution for metro construction are made by very limited number of experts. Instant risk identification

of risk management of metro and underground construction can be accomplished using an safety risk identification system (SRIS) based on construction drawings and risk identification rules to identify potential safety hazards, identify risks automatically and provide a basis for early warning and risk control (Ding *et al.* 2012).

In construction phrase, a web-based system was developed for safety risk early warning in urban metro construction and validated on several projects in China. A hybrid data fusion model based on multisource information (monitoring measurements, calculated predictions, and visual inspections) was employed to automatically imitate human experts giving safety risk assessment and early warning (Ding, Zhou 2013). To predict safety conditions on the construction site based on a multidimensional data model, a safety-oriented geotechnical instrumentation data warehouse was established integrating all data from heterogeneous sources for quick retrieval of information on site and for accident prevention (Ding *et al.* 2014).
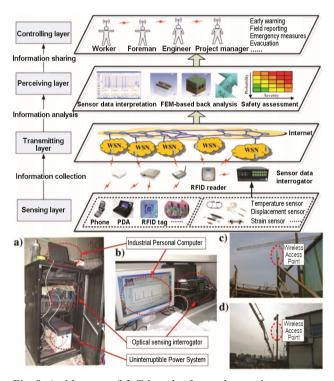

Fig. 8. Architecture of IoT-based safety early warning system and transmitting devices at the construction site (Ding *et al.* 2013b)

In order to improve web-based tools for construction safety management, "Internet of Things" (IoT) technology was introduced to create a sensor-saturated networked environment on a construction site, see Figure 8. With the seamless integration of a Fiber Bragg Grating (FBG) sensor systems and a RFID-based labor tracking systems, a comprehensive metro construction safety control system and devices were initially developed to overcome the risk control lags in the in construction process and verified through an application at the crossing passage in the Yangtze Riverbed Metro Tunnel project (Ding *et al.* 2013b). In addition, the research team deve-

loped an original virtualized safety risk spatial-temporal coupling system to break through bottleneck of relying on single warning index for metro construction management based on BIM technology. So safety status of related components could be continuously visualized as conditions changed and potential safety risks evolved (Zhou *et al.* 2013a).

2.3.3. Laser scan and range point cloud for spatial information acquisition

For point cloud data acquisition and processing, accurate and rapid assessment of the as-built status on a construction site provides the opportunity to understand the current performance of a project. Rapid project assessment further identifies discrepancies between the as-built and as-planned progress, and facilitates decision making on the necessary remedial actions. To improve error-prone and time-consuming ways of conventional visual observations and surveying, research on automatic recognition of as-built condition and visualization of construction progress was conducted. For better accuracy and efficient data acquisition, performance evaluation of an Unmanned Aerial Vehicle (UAV) for mobile, rapid and autonomous acquisition of three-dimensional (3D) mapping data was carried out (Siebert, Teizer 2014), as shown in Figure 9. The combination of wireless communication with three-dimensional laser scanning helps to realize image collection and display, image editing and analysis of the tunnel face, tunnel stability monitoring and personnel orientation management (Ye *et al.* 2009).

Efforts are made for robust automated recognition/ retrieval of 3D CAD objects in range point clouds in the Architectural/Engineering/Construction & Facility Management (AEC-FM) context. However, more questions remain to be addressed and additional research is required for algorithms that automatically extract conventional or parametric CAD objects from laser scanners or image-based point cloud models.

Fig. 9. An Unmanned Aerial Vehicle (UAV) for mobile and autonomous acquisition of for 3D mapping of built infrastructure (Siebert, Teizer 2014)

A 3D laser scanning of the earth's surface and a global positioning system (GPS) to obtain global geographic coordinates was presented for applications in construction projects through acquisition of landslide data and computing of earthwork volumes. Although thus calculated volumes may not be accurate when compared to conventional methods such as triangulation, field and office durations of operations could be reduced (Du, Teng 2007).

As the visibility of personnel and vital materials on construction sites are essential to equipment operators, the blind spots of construction equipment should be care-

fully identified as part of the instruction routine in operator training. An automated blind spot detection tool was presented that determines the equipment blind spots rapidly and in 3D through analysis the point cloud data from a laser scan inside the equipment cab (Teizer *et al.* 2010), see Figure 10. Other application and practice of using point cloud data of equipment were presented and validated in a tunnel deformation monitoring (Wu *et al.* 2013b).
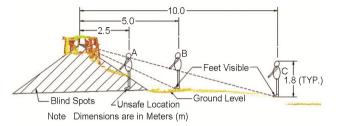

Fig. 10. Worker's visibility at different locations (A, B, and C) close to equipment (Teizer *et al.* 2010)

A synthesis method for multiple-attribute decisions has been proposed to increase the correctness of the rendered decisions by assessing alternative construction, technological and occupational safety solutions in uncertain jobsite conditions (Simanaviciene *et al.* 2012, 2014). Also, a multi-stage decision model reflecting a set of available combinations of alternatives has been developed to evaluate the effect of each criterion and its interaction with other criteria, which in turn assists with choosing appropriate solutions for structural design, construction technology and work safety challenges at hand (Liaudanskiene *et al.* 2012).

Conclusions and future research

Conclusions

Information technology has been applied in a wide array of applications to provide solutions to construction safety problems. Efforts made by researchers to assess the occupational safety (Dėjus, Antuchevičienė 2013), monitor performance of workers, equipment and construction environment, to replace human operations with robots and to collaborate among themselves are vital in creating a safe-working environment and in reducing casualties (Shin *et al.* 2014; Moon *et al.* 2014a; Ma *et al.* 2014; Kim *et al.* 2014; Han *et al.* 2014; Guo *et al.* 2014; Fung *et al.* 2014; Choe *et al.* 2014; Zhu *et al.* 2013; Zhang *et al.* 2013a; Ye *et al.* 2013; Wu *et al.* 2013a; Wang 2013; Sparer, Dennerlein 2013; Sepasgozar, Bernold 2013; Schikora *et al.* 2013; Rubio-Romero *et al.* 2013; Qin 2013; Melzner *et al.* 2013; Marzouk, Ali 2013; Marks *et al.* 2013; Luo *et al.* 2013; Li *et al.* 2013; Kivrak *et al.* 2013; Kim, Park 2013; Kasirossafar, Shahbodaghlou 2013a; Hinze *et al.* 2013; Hammad *et al.* 2013; Ding *et al.* 2013a, 2013c; Zhou *et al.* 2012; Zhao *et al.* 2012; Zhao, Ye 2012; Yang *et al.* 2012; Ren *et al.* 2012; Li, Hua 2012; Li *et al.* 2012a; Huang 2012; Hamidi *et al.* 2012; Gao *et al.* 2012; Esmaeili, Hallowell 2012; Yang, Ma 2011; Xue *et al.* 2011; Wang *et al.* 2011; Tang,

Yamada 2011; Shen, Zhu 2011; Maalek, Sadeghpour 2011; John, Ganah 2011; Guo *et al.* 2011; Golparvar-Fard *et al.* 2011; Ding *et al.* 2011a, 2011b; Chen *et al.* 2011; Aguilar, Hewage 2011; Yang *et al.* 2010; Yamamoto *et al.* 2010; Talmaki *et al.* 2010; Syachrani *et al.* 2010; Qi *et al.* 2010; Patel *et al.* 2010; Meng *et al.* 2010a, 2010b; Hu *et al.* 2010a, 2010b; Dobrzański, Pasternak 2009; Ding *et al.* 2010; Cheng *et al.* 2010; Zhang *et al.* 2009; Wang, Q. K., Wang, S. Q. 2009; Park *et al.* 2009; Lv, Zhu 2009; Teizer *et al.* 2008, 2007; Teizer, Castro-Lacouture 2007; Teizer 2007; Li *et al.* 2007; Nuntasunti, Bernold 2006; Cho, Youn 2006).

Research on sensors for fast and accurate tracking of construction resources for construction safety management was actively pursued in the past 14 years. Strategy for deployment of RFID sensor networks and their performance were among the most frequently discussed topics. A variety of technologies offered diverse capabilities for enhancing the overall safety performance. ZigBee, UWB, GPS, WLAN, and 3D virtualization technologies complement one another to increase reliability and timeliness of sensing and tracking locations in indoor or outdoor scenarios. Thus, it was worthwhile to examine the potential of hybrid systems comprising multiple technologies (Hwang 2012). Research in choosing and combining these technologies for most cost effective applications has been expected. For fast as-built status determination and compliance analysis, 3D laser scan technology was determined to be an efficient first step for spatial information acquisition. However, the accuracy and timeliness for automated recognition and retrieval of 3D BIM components from point clouds for dynamic construction process and object modeling remain to be studied further.

As demonstrated in Section 2, sensor-based systems, robotics and manipulators, and other IT-based systems are the three main research topics of the past decade in the realm of IT-based construction safety management. These technology-related aspects are closely connected to one another for achieving safe construction tasks, particularly with sensory data-saturated networks of on-site equipment.

The compilation conducted indicates that the leading research institutions contributing most of the last decade's research on IT-based construction safety performance solutions were Georgia Institute of Technology (Georgia Tech) and Huazhong University of Science & Technology (HUST). Researchers led by Dr. Jochen Teizer, formerly at Georgia Tech in Atlanta, USA, and currently at STRABAG SE in Stuttgart, Germany, focused on real-time resource location tracking based on mobile laser scanning, automated three-dimensional as-built modeling, advanced safety for heavy equipment operation and work sites, virtual decision making environments, and safety performance learning tools. HUST Professor Lieyun Ding dedicated his team's activities to research on safety risk identification and risk containment in metro construction projects. Researchers on Professor Ding's team developed a metro construction safety control

system and conducted research on lifecycle dynamic safety control for built infrastructure.

Future research

The use of BIM-based mobile applications will bring more interoperability and flexibility to field construction management. The combination of BIM and GIS technologies will create more location-based applications with the potential to integrate multiple BIM-based projects on a larger scale such as a city subdivision, municipal administrative units, and at even higher levels of jurisdiction. Also, precise indoor object recognition will help establish the corresponding relationship between as-build components and BIM elements for construction safety compliance verification.

A look at the on-going research awarded by USA and China's National Science Foundation (NSF) provides a perspective on government policies on science and technology in regard to IT-based construction management. More details are likely to become available upon the completion of the ongoing research in the USA and China as the corresponding authors from these two countries have historically contributed most of the articles on this particular topic.

In the last three years, there have been four new US National Science Foundation-supported research projects related to construction safety:

1. AIR Option 1: Technology Translation: Development and Evaluation of Field Prototype for Determining Excavator Proximity to Buried Utilities (University of Michigan, 2013);
2. GOALI: Geo-referenced Visualization and Emulated Proximity Monitoring for Real Time Knowledge-Based Excavator Control (University of Michigan Ann Arbor, 2012);
3. Collaborative Research: Correlating Geospatial Data Lineage and Positional Accuracy for Excavation Damage Prevention (Purdue University, 2013);
4. Collaborative Research: Automatic Behavior Monitoring for in-Depth Analysis of Construction Fatalities and Injuries (University of Michigan Ann Arbor, 2012).

In the last three years, China's National Science Foundation has funded the following seven construction safety projects:

1. Research on organization network model and case study of civil engineering construction safety knowledge sharing (HUST, 2014);
2. Behavior Simulation model and its application based on system dynamics modeling and multi-agent modeling related to civil engineering construction safety (Tsinghua University, 2014);
3. Study on the mechanism of unsafe behavior of construction workers and their application in construction safety management (Tsinghua University, 2013);
4. Construction safety control theory and method of metro adjacent bridge (Beijing Jiaotong University, 2014);
5. Study on the tunnel construction safety and control mechanism of blasting in confined space (Beijing Jiaotong University, 2013);
6. Metro safety monitoring data reconstruction and construction safety risk assessment based on Compressed sensing (HUST, 2013);
7. Study on impact of stakeholders behavior on construction safety mechanism and organizational behavior modification (China University of Mining & Technology, 2011);
8. Research on real time early warning safety control of metro tunnel deformation based on uncertainty theory and Bayesian network (HUST, 2014).

Nearly half of the ongoing research focuses on underground construction safety management due to a massive volume of metro construction activities in China and their associated safety issues. Much of this effort has been reported in recent issues of various journals but not explicitly reviewed in this paper. The complexity and uncertainty of large-scale metro construction brings more technical and managerial challenges such as adjacent building foundation protection, severe geological conditions, tight construction schedules, newly applied innovative construction methods create new opportunities for current and future construction safety engineering and related IT research.

Acknowledgments

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Miroslaw J. SKIBNIEWSKI. Professor, leads the e-Construction Research Group in the Department of Civil and Environmental Engineering at the University of Maryland in College Park, USA. A former Professor and Assoc. Provost at Purdue University in West Lafayette, Indiana, USA, he holds a MEng degree in Civil Engineering from Warsaw University of Technology in Poland, and MS and PhD degrees in Civil Engineering Planning and Management from Carnegie Mellon University in Pittsburgh, Pennsylvania, USA. He is an author or co-author of over 200 research articles on a wide array of topics related to information technologies and automation for the construction industry. Prof. Skibniewski's research has been supported by the U.S. National Science Foundation, SAP-America, Fulbright and Humboldt Foundations, Bechtel Corporation, Obayashi Corporation and the Clark Construction Group, among others. He has been a recipient of the U.S. National Science Foundation's Presidential Young Investigator Award, American Society of Civil Engineers' Walter L. Huber Research Prize and the International Association for Automation and Robotics in Construction Tucker-Hasegawa Award for lifetime research achievements in construction automation. Prof. Skibniewski holds an honorary doctorate from Vilnius Gediminas Technical University.