Towards the "Third Wave": An SCO-enabled Occupational Health and Safety Management System for Construction

Yuhan Niu, Weisheng Lu, Fan Xue, Diandian Liu, Ke Chen, Dongping Fang, and Chimay Anumba

This is the peer-reviewed post-print version of the paper:

Niu, Y., Lu, W., Xue, F., Liu, D., Chen, K., Fang, D., & Anumba, C. (2019). Towards the "third wave": An SCO-enabled occupational health and safety management system for construction. *Safety science*, *111*, 213-223. Doi: 10.1016/j.ssci.2018.07.013

The final version of this paper is available at: https://doi.org/10.1016/j.ssci.2018.07.013.

Abstract

Occupational health and safety (OHS) is of the utmost concern in the construction sector. For decades, researchers and practitioners have endeavoured to enhance construction OHS performance through various measures ranging from "hard" technologies (in this paper, the "first wave" of construction OHS management) such as provision of personal protective equipment, to the more recent "soft", managerial approaches (the "second wave") such as fostering a safety culture. Although considerable improvements have been made in construction OHS, the general sentiment is that construction remains one of the most dangerous sectors, warranting more innovative or even revolutionary approaches. This research seeks to develop a smart construction object (SCO)-enabled OHS management system. The central tenet of the system is that artificial intelligence (AI), as the art of creating machines that perform functions that require intelligence when performed by people, represents a direction of the "third wave" in construction OHS management. The system embraces emergent SCOs and harnesses the power of their smart properties of awareness, communicativeness, and autonomy. The system is demonstrated and validated in real-life construction practice and a controlled lab test with a tower crane, the cause of many construction-related injuries and fatalities, as the subject. It is found that the SCO-enabled OHS management system can identify dangerous situations and respond to them autonomously. This research suggests that smarter construction, through incorporation of AI in particular, is a direction of much promise in terms of improving construction OHS.

Keywords: Occupational health and safety (OHS); construction safety; smart construction object (SCO); tower crane; artificial intelligence (AI)

1. Introduction

According to the International Labour Office (2001), OHS management refers to a coordinated and systematic approach undertaken by an organization to protect the safety and health of all members through prevention of work-related injury, illness and disease. Despite strenuous efforts to manage OHS in the construction industry, its safety performance is still alarmingly poor. In the United States, for example, construction accounted for no more than 5 per cent of the workforce but 20 per cent of occupational deaths in the years 2003 to 2013 (National Safety Council 2015). This disproportionate pattern is similar or worse in developing economies (Raheem and Hinze 2014). It is estimated that a total of 60,000 construction fatalities occur every year around the world; on average, one every nine minutes (Somavia 2005). The construction industry, while "instrumental in influencing human health, economic activities and social behaviour as well as cultural identity and civic pride" (Pearce 2003), is also one of the most dangerous.

Efforts of researchers and practitioners to improve construction OHS management have been ongoing across several historical stages of development. The early days of OHS management can be characterised by a reliance on "hard" protection, using personal protective equipment (PPE) as a physical buffer between users and hazards. This was termed the "first wave" of OHS management in this paper. With the growing attentions on the root causes of accidents, a "second wave" of construction OHS management arises with the emphasis on safety training and safety education to reduce unsafe behaviours and dangerous situations. While considerable progress has been achieved during the first and second waves, often insufficient for making rational decisions and taking appropriate action when dangers suddenly emerge, making alerts ineffective. As a consequence of such limitations, construction around the world is witnessing stagnant OHS management. Inspired by smart technologies (e.g., artificial intelligence [AI], robotics) in other sectors, the construction industry is also vigorously exploring how these technologies as having the capacity can provide a revolutionary approach to improving OHS management in construction. This AI-based OHS management is to be argued as the "third wave" development in construction.

However, the understanding of this "third wave" is in its infant stage. For example, there are exhortations to develop full "AI", or totally disruptive solutions to construction OHS management, while the take-up of these advocacies is rather low in reality.

Building on previous studies of smart construction objects (SCOs), the primary aim of this research is to (a) develop a SCO-enabled construction OHS management system, and (b) argue that SCOs augment construction resources with a "narrow AI" should be the "third wave" development of construction OHS management. Central to the "third wave" of construction OHS management is not completely departing from existing OHS management methods. While acknowledging the adoption of PPE and importance of preventive strategies, an active AI-based solution is proposed with the deployment of smart construction objects (SCOs). While SCOs provide OHS-related decision-making information to human decision-makers, they can also talk to each other directly. Thus, actions that can eliminate a hazard at source can be taken by SCOs promptly and autonomously; that is, without necessarily involving human decision-makers in the loop.

The remainder of this paper comprises seven sections. Subsequent to this introductory section is a review of the literature on the revolution of construction OHS management. By introducing the definition and properties of SCOs, the potentials and advantages of using SCOs for OHS management are presented in Section 3. In Section 4, the architecture and workflow of an SCO-enabled OHS management system is presented. With a tower crane selected as the target, the system is prototyped and validated in the context of a real-life on-site project in Section 5. A lab experiment is also presented demonstrating the system and how the SCO-enabled OHS management framework could be used in management strategy development. Section 6 discusses the prospects and challenges of the SCO-enabled OHS management framework, and conclusions are drawn in Section 7.

2. The three "waves" development of construction OHS management

The early days of OHS management can be characterised by a reliance on "hard" technologies, which is termed as the "first wave" OHS management in this paper. The protection is mainly relied on physical buffers provided by personal protective equipment (PPE) such as safety helmets, boots, gloves, and goggles (Hinze et al. 2013). Fundamentally, PPE work in the way of imposing a barrier between the user and the working environment, thus reducing the user's exposure to hazards including physical, electrical, heat, chemicals, biohazards, and airborne particulate matter. The "first wave" OHS management is not uniquely used in construction. A cross-sectoral analogue is the automotive industry, where car manufacturers have adopted physical protection (e.g. safety belts, air bags, and anti-lock braking systems) to protect drivers and passengers.

Despite the widespread applications of PPE in construction and continuing advances in technological approaches to its provision, a general limitation of PPE is that it does not eliminate hazards at their source (Holt 2008). Thus, significant efforts have been directed in recent years to investigating the root causes of accidents. Heinrich (1941), a pioneer in accident causation investigation, developed the domino theory, which states that injuries occur as a result of linear, sequential factors. Building on this theory, enriched causation models incorporate factors such as unsafe conditions, unsafe behaviour and worker response (Abdelhamid and Everett 2000). Managerial approaches to tackling these causes have also been explored, such as developing a behaviour-based safety system (Choudhry and Fang 2008), conducting safety training (Hadikusumo and Rowlinson 2002), and fostering a safety culture (Mohamed 2003) and climate (Hahn and Murphy 2008). These efforts echo developments attributing accidents largely to overload of human capabilities, both physical and psychological, such as the human-error causation model (Petersen 1984) and the DeJoy (1990) model. While unavoidably intertwined with traditional technological approaches, such efforts focus on "soft" aspects and can be collectively referred to as the "second wave" in OHS management. As in the case of "hard" technologies, an emphasis on "soft" aspects can also be found in the automotive industry, for example through safe-driver education and the enforcement of strict traffic rules and regulations.

While human error-related accidents can be reduced with safety training and safety culture development, they cannot be completely eliminated due to unexpected conditions such as fatigue or sudden site distractions (Fang *et al.* 2015). Studies have been made for safety management systems using emerging technologies, most of which focus on detecting hazardous conditions and issuing alerts. For example, sensing technologies such as Radio Frequency Identification (RFID) (Lu *et al.* 2011; Flanagan *et al.* 2014) and wireless networks such as ZigBee have been used to capture real-time construction site conditions (Wu *et al.* 2010), while cyber-physical systems have been developed to model the complexities of construction safety (Yuan *et al.* 2016). Alerts can be issued when people enter pre-defined danger zones (Yang *et al.* 2012) or are too close to moving objects (Teizer *et al.* 2010).

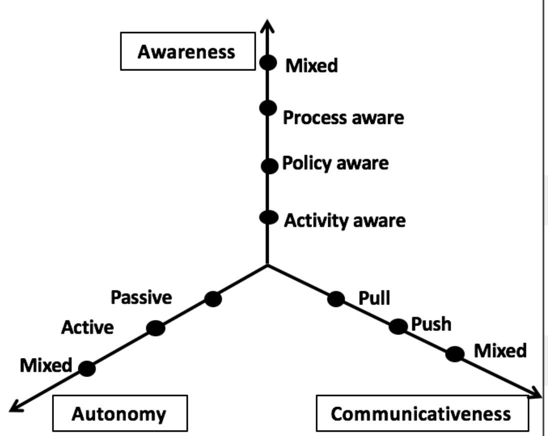
However, the safety protection provided by these technologies is imperfect. Although timely alerts can be provided, in-time mitigations and actions in response to dangerous situation still largely rely on humans. Researchers have theorized OHS management as decision making, recognizing that the rationality of human decision-makers (e.g. safety managers and construction workers) is generally bounded by a “triangle of limits” (Simon 1976): available information, cognitive ability, and finite amount of time. The latter is often insufficient for making rational decisions and taking appropriate action when dangers suddenly emerge, making alerts ineffective. Thus, a more intelligent, in-time solution is desired to manage OHS events proactively and promptly.

The development of construction OHS management, toward the next wave, could draw inspiration from the automotive industry. Smart systems such as self-parking and collision prevention assistants are now embedded in cars to improve driving safety, for example by detecting hazardous conditions and alerting drivers. These smart systems are enhanced with artificial intelligence (AI) in auto-pilot systems (e.g. as in Tesla vehicles) (Kessler 2015) and autonomous vehicles (e.g. Apple self-driving cars) (Harris 2015). Since movement on the road is no less complex than on a construction site, there are no barriers to the exploration of AI in construction OHS management. It is thus proposed the “third wave” of construction OHS management, in this study, subscribes to AI-based solutions. It acknowledges that human beings are not infallible, but rather, show deficiencies (such as being slower and more error-prone) when compared with AI in processing information and making prompt actions (Sterman 1989; Reason 2000).

3. SCOs for OHS management

Proposed by Niu *et al.* (2015), smart construction objects (SCOs) represent a new way of capturing, processing, and communicating information to support decision making in construction. SCOs are “construction resources (e.g., machinery, tools, devices, materials, components, and even temporary or permanent structures) that are made smart by augmenting them with sensing, processing, and communication abilities so that they have autonomy and awareness, and can interact with the vicinity to enable better decision making" (Niu *et al.* 2016). Instead of introducing a completely new system to construction sites, an SCO-enabled management system relies on construction objects (such as machines, materials and components) already involved in the construction process. Without compromising their original appearance and function, these objects are augmented with smart and interconnected properties. For example, a smart excavator may be able to locate and report its real-time position without demanding extra room while still performing the excavation job.

The three core properties of SCOs, awareness, communicativeness, and autonomy, refer to SCOs' abilities in sensing, data exchange, and action-taking, respectively (Niu *et al.* 2015). Each core property is further categorized into sub-properties with different functions (elucidated by a tri-axial diagram and summative table in Fig. 2), the utilization of which allows the potentials of SCOs for OHS management to be achieved. For example, by applying activity awareness, SCOs could help record the number of times and the frequency of machine operations. Comparatively, policy awareness enables SCOs to detect whether there is a break of limit in loading or other critical factors. The SCOs' communicativeness ensures that these conditions are conveyed to people comprehensively and in a timely manner, either passively or proactively. In addition, depending on the type of autonomy, SCOs have the potential not only to issue alerts but also to take action in case of emergencies.



Awareness	**The ability of SCOs to sense and log the real-time condition of SCOs and the surrounding environment**
Activity aware	To understand a and make a record when a certain type of activity or event is triggered
Policy aware	To understand to what extent the real-time condition or activity complies with rules and regulations
Process aware	To understand and recognize the workflow and transition between construction activities
Mixed	To have more than one type of above awarenesses
Communicativeness	**The ability of a SCO to share information with managerial personnel or other SCOs**
Pull	To provide information on request
Push	To proactively send updated information or issue alerts in a regular interval
Mixed	To have both pull and push communicativeness
Autonomy	**The ability of SCOs to alert people of the need for actions or to take actions autonomously**
Passive	To alert people and to assist people in making decisions and taking action
Active	To take self-directed action proactively based on change of conditions
Mixed	To have both passive and active autonomy

Fig. 2. The core properties of SCOs

Together, the smart properties of SCOs offer a new avenue for advancement of construction OHS management that is not completely departing from existing OHS management methods while adding AI-based values. From the perspective of the "first wave" of OHS management, using SCOs is not an abandon of PPE. Since SCOs is primarily making existing construction recourses smarter, the functions of SCOs is still "lodged in" PPE and other construction objects. Looking at SCOs from the "soft" OHS strategies, it focuses on the dangerous situations as one of the leading causes for accidents and injuries. The application of SCOs aims to take active and preventive safe-guarding actions when dangerous situations are detected. Nevertheless, rather than comprising a new, ambitious centralized system with artificial general intelligence, or "full AI", capable of performing any human intellectual task (Kurzweil 2005), SCOs could augment construction resources with a "narrow AI" that equals or exceeds human intelligence with regards to specific tasks. The rationale and workflow of SCOs will be articulated in details as follows in the SCO-enabled OHS management system.

4. The SCO-enabled OHS management system

In this paper, a multi-layered SCO-enabled OHS management system is proposed. The architecture of the system is shown in Fig. 3. At the shopfloor layer are the construction objects (e.g. precast facades or machinery) that are augmented into SCOs. A smart core integrating various sensors, communication modules, and actuators (e.g. GPS, IMU, Bluetooth, and LiDAR) is installed in or attached to the construction objects, endowing them with the three core SCO properties of awareness, communicativeness, and autonomy. Dangerous situations to be detected and the SCO-based solutions are stored in the respective databases, which are centrally managed in the smart management platform (SMP). Pre-existing conditions of dangerous situations can be input into the event database, which could be continuously expanded and updated with newly emerging industry-reported events. Based on updated conditions in the database, relevant SCO solutions can be revised to guide the applications in the top layer. The SMP also incorporates a BIM-oriented database so as to relate the conditions to ongoing projects and identify the possible impacts of these conditions on overall project performance. An online monitoring interface is established in the SMP for visualization purposes with Cesium (ver. 1.24). The smart applications enabled by the sensing, communicating, and action-taking abilities of SCOs are specified in the application layer. These applications will be designated to sensors and actuators based on the application scenarios, which are directly executed by SCOs. Each application is also supported by the SMP, which can provide human decision-makers with visualized data and prompt alerts.

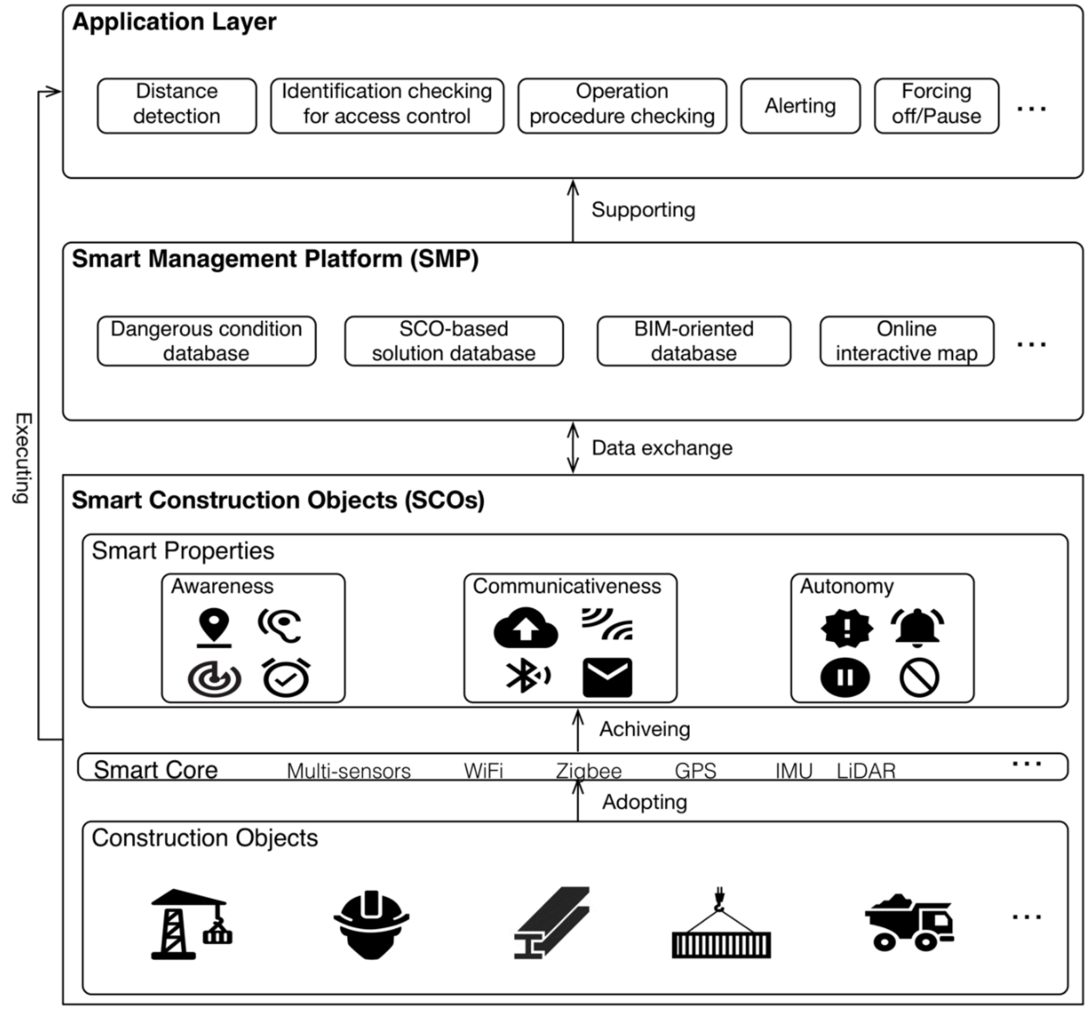


Fig. 3. The architecture of the SCO-enabled OHS management system

A generic SCO workflow in dealing with the dangerous situations is outlined Fig. 4. It is similar to the logic behind the software that makes the OHS management system operable. The workflow is "generic" in the sense that it is expected to be sufficiently inclusive to embrace all sorts of typical scenarios in construction OHS management. The conditions of dangerous situations (e.g. hoisting materials) that may induce accidents or injuries are constantly sensed using SCO awareness. For situation, there will be a series of pre-set conditions against which to gauge whether the condition hits a threshold or not. If not, the SCOs will continue sensing. When an condition sensed by the

SCO is diagnosed as dangerous, respective communicativeness and autonomy solutions will be triggered. In the SCO-based OHS management system, each SCO-based solution is assigned a set of communicativeness and autonomy sub-modules. The communicativeness sub-modules will communicate the diagnosed situation to the SMP, searching suitable autonomy sub-modules. Clear rule-based decisions such as halt or force quit can be autonomously made by SCOs without necessarily involving human decision-makers in the loop. Where no active autonomy is available, passive autonomy will be triggered to alert human decision-makers. Records of emerging conditions are constantly logged and pushed to the SMP, assisting further data analysis. Compared with the human decision-making process, SCO awareness and decision-making can occur instantaneously, making the subsequent SCO-enabled reaction concurrent or near concurrent. This SCO-enabled concurrence, *vis-à-vis* most prevailing "ex-ante" training or "ex-post" analyses, could more effectively prevent dangerous situations from developing into serious accidents.

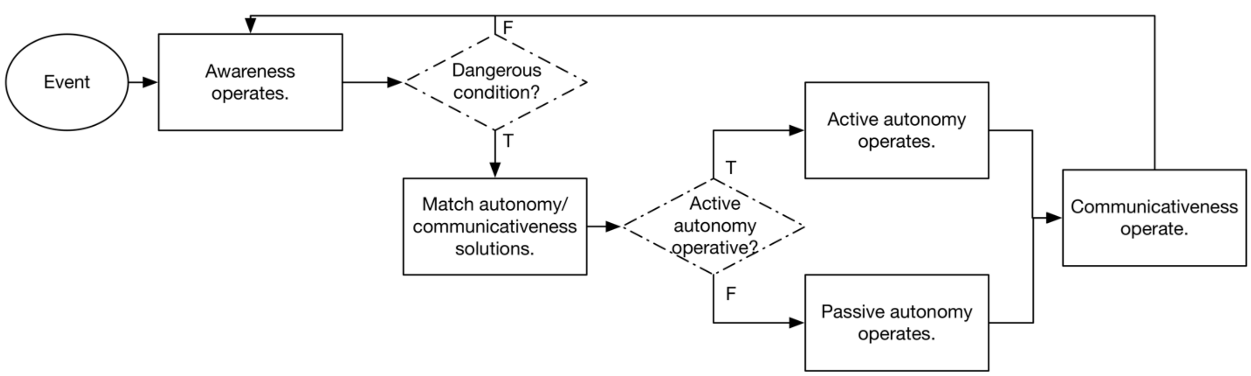
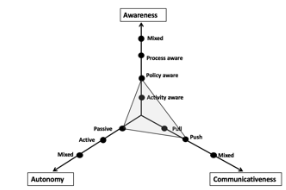
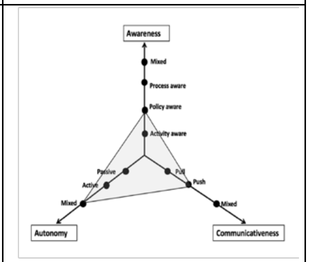
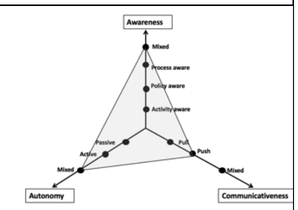
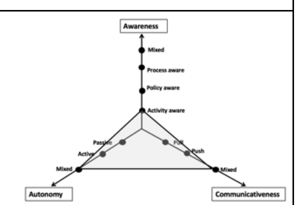
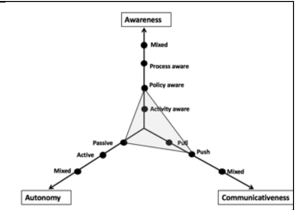


Fig. 4. A generic SCO-enabled OHS management workflow

A few examples of how dangerous situations are managed according to the workflow are provided in Table 1. While by no means exhaustive, these are based on most-commonly occurring and most-often addressed hazardous events that are prone to deteriorate into accidents identified from the literature (Cambraia *et al.* 2010; Green and Tominack 2012; Wu *et al.* 2010; Yang *et al.* 2012) and reports (OSHA 2011a, 2011b, 2011c, and 2011d). Against each listed event, the potential SCO-based solutions that can be deployed and the associated workflow are demonstrated and explained as follows.

Table 1. The examples of events to be managed by the SCO-based OHS management system

Events to manage	SCOs	Pre-set condition for awareness	Dangerous situations	Awareness	Communicativeness	Autonomy	Triaxial diagram of SCOs
(a) Failure to maintain safe distance between on-foot worker and restricted area	Smart PPE	Distance detection between worker and restricted area	Distance ⩽ buffer distance	Policy awareness	Information push	Passive autonomy	
(b) Failure to maintain safe distance from parts of machine/vehicle	Smart PPE and moving parts of machine/vehicle	Distance detection between worker and moving parts	Distance ⩽ buffer distance	Policy awareness	Information push	Active autonomy	
(c) Incorrect operation/Improper use of machine for critical procedures	Smart machine and equipment	Critical factor sensing and operation process detection	Factor value ⩾ threshold ± buffer range; incorrect operation procedures	Mixed awareness (policy awareness and process awareness)	Information push	Mixed autonomy	
(d) Failure to check/maintain equipment on time	Smart equipment	Checking the total time / frequency of usage	Time / frequency ⩾ threshold	Activity awareness	Mixed communicativeness	Mixed autonomy	

(e) Critical environmental factors beyond human-bearing threshold	Smart PPE	Sensing the critical environmental factors	Factor value ⩾ threshold ± buffer range	Policy awareness	Information push	Passive autonomy	

(a) Failure to maintain safe distance between on-foot worker and restricted area

Most dangerous situations related to falls, electrocution, and "caught-in between" events are associated with workers getting too close to hazardous areas such as edges at high levels, trenches without shoring, and working radii of derricks or cranes. In these circumstances, the personal protection equipment (PPE) of workers, such as safety helmets, could be made into SCOs able to sense the real-time location of these workers at all times. Applying SCO policy awareness, geographical location is set as a threshold with a buffer range in the periphery. When a worker steps into the buffer range, the smart PPE item issues an alarm via passive autonomy, alerting the worker so that he/she proceeds no further.

(b) Failure to maintain safe distance from moving parts of machines/vehicles

Occupational Safety and Health Administration (OSHA) reports reveal that workers can easily be struck when passing a machine/vehicle operation without keeping a safe distance, whether due to carelessness of the worker or the operator. If a worker stands within the swing range of a moving part of a machine, he/she can be caught between the machine and a solid object, such a wall or another piece of equipment. To manage such scenarios, both workers' PPE and the moving parts of machines/vehicles can be transformed into SCOs able to constantly calculate the distance between them. These machines/vehicles can be augmented with electrical brakes which activate when the SCOs detect border-crossing passers-by, thereby preventing accidents.

(c) Incorrect operation/ Improper use of machines for critical procedures

Turning construction equipment and machines into SCOs enables prevention of their incorrect operation and improper use. Mixed awareness, mixed autonomy and information push can be applied to cover a diverse range of dangerous situations. For example, loading capacity, rotation angle, and lifting height of a tower crane can be set as policy awareness thresholds to prevent overloading or hoisting in multiple directions simultaneously. For non-critical procedures, the operator can be alerted via passive autonomy; at the same time, standard procedure instructions can be pushed to the operator. In the case of critical procedures, equipment can be compulsorily locked or turned off until the necessary corrections are made.

(d) Failure to check/maintain equipment on time

Failure to undertake regular examination and maintenance of equipment, especially of heavy machinery, has significant safety and cost implications for construction. When items of equipment are turned into SCOs, activity awareness can sense and assist in the precise recording of each activity related to their use or handling, such as picking up, turning on, and operating. A typical case of activity awareness is presented in Fitton *et al.* (2008), where a pay-per-use function was enabled by sensors in road patching machines. For regular examination and maintenance purposes, a mixed communicativeness is chosen. Here, the SCOs actively push information at regular intervals, while the machine use record can be pulled out manually when needed. Alerts are made via passive autonomy when maintenance is required based on handling time. If no subsequent maintenance is undertaken, the SCOs will use active autonomy to intervene by forcing users off the equipment or locking it into standby mode.

(e) Critical environmental factors

Proposals for environment-based construction OHS management solutions have been made since SCOs were first discussed in Niu *et al.* (2015). SCOs enable monitoring of critical environmental factors that are hazardous to workers or machine operations. Monitoring non-perceptible factors such as toxic vapours, for example, can reduce the occurrence of diseases such as pneumoconiosis or asbestos-related lung cancer. For critical environmental factors, maximum human-bearing thresholds can be input into smart tools and PPE. Augmented with policy awareness, these SCOs can sense environmental conditions and, if conditions are below the threshold, perform information push to the management platform for monitoring. If the threshold is crossed, the SCOs can use passive autonomy to alert workers.

5. Demonstration and validation

5.1 Background

To demonstrate and validate the proposed SCO-enabled OHS management system, the operation of tower cranes was explored. Tower cranes hoist and transport a variety of loads near and above construction workers, often working in crowded conditions and occasionally with overlapping work zones. The use of tower cranes can increase safety risks on sites that are already inherently hazardous (Shapira and Lyachin 2009, Raviv and Shapira 2018), as well as threatening pedestrians

(Shepherd *et al.* 2000). Estimates suggest that cranes are involved in up to one-third of all construction and maintenance fatalities (Neitzel *et al.* 2001); therefore, the importance of tower crane management in improving overall construction safety performance cannot be over-emphasized.

Prevailing OHS management practice in tower crane operations is highly dependent on individual experience rather than scientific evidence. While experience is extremely important in construction, overconfidence in this experience means that evidence-based decision making is lacking. Ongoing tower crane operation conditions are reported and recorded by contractors sporadically, if at all. Although some studies have used data obtained from statistical reports as a reference for accident prevention (e.g. Chi and Han 2013, Tsang et al. 2017), such data may be unreliable due countless unreported incidents; in addition, such statistics are unable to provide information on root causes , as well as being questionable predictors of accidents (Shapira and Lyachin 2009). Post-accident analysis also has limited power in preventing recurrence. The proposed SCO-enabled OHS management system offers a means of capturing and recording more reliable, real-time or near real-time, comprehensive data covering target conditions in tower crane operations. It also provides impetus for AI applications providing in-time mitigation of dangerous situations in construction OHS management.

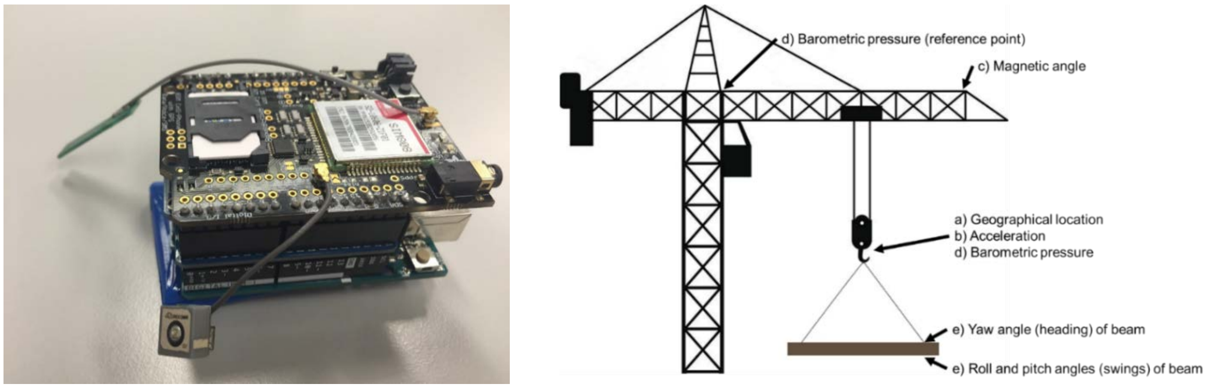
5.2 Field test

Discussions with construction managers revealed five commonly occurring dangerous situations related to tower crane operation (see Table 2), all of which could lead to serious accidents if not handled properly. Hook over-height could cause equipment damage when hoisting heavy loads, or in extreme cases tip the crane. Crossing of the jib and trolley into restricted areas may result in collisions with surrounding machinery, buildings, or people working at heights. Unbalanced hoisting and lifting heavy weights over dynamic restricted areas (e.g., personnel work zones, areas containing assets and equipment) are both serious, dangerous situations which could easily cause objects to fall as loads become out of control. The conditions to be sensed and criteria for alert/action for each dangerous situation in our field test are listed in Table 2.

Table 2. Dangerous situations and related tower crane operation conditions managed in the field test

Dangerous situations	**Real-time data of conditions**	**Criteria for alert/action**
(1) Hook over-height	Height of hook	Hooking height ≥ height threshold
(2) Jib/Trolley/Load crossing pre-set restricted areas	Slewing angle of jib, distance of trolley, swing motions of load	Jib slewing angle entering a constant range of angles
(3) Jib/Trolley/Load crossing dynamic restricted areas	Slewing angle of jib, distance of trolley, swing motions of load and its geo-position in relation to moving personnel and vehicles in the zone	Jib slewing angle entering a constant range of angles, and heavy load moving over dynamic restricted zones of personnel and vehicles
(4) Unbalanced hoisting	Motions of jib, trolley, and hook	Simultaneous motions of jib, trolley, and hook
(5) Over-swing of load	Swing motions of beam	Swing angle ≥ swing threshold

Several smart cores were developed for the field test, each consisting of a microcontroller, an inertial measurement unit (IMU), a GPS module, a barometer, an anemometer, and a global system for mobile communication (GSM) module. These smart cores were mounted to the key components of a tower crane and the hoisted object to make them smart. No prior knowledge existed regarding where to mount the smart cores, or what to collect to sufficiently capture tower crane operations and subsequently identify dangerous situations for alert and intervention purposes. Therefore, this process was discussed with site managers and conducted through trial and error. Figure 5 shows a feasible installation scheme using a smart core adopted, without suggesting it is the only and best scheme to do so. The figure shows the smart core installation positions, while the table shows what data is collected through which sensing modules for monitoring and diagnosing specific dangerous situation. At this point in the field test, the conventional tower crane and its materials had been turned into SCOs through the use of smart cores (c.f. Fig. 3) and it could now function with extra smartness through awareness, communicativeness, and autonomy.



Sensing Module		Monitoring Index/Data		Indicators for dangerous events
GPS	→	a) Geographical location		Distance of trolley
Accelerometer (IMU)	→	b) Acceleration		Slewing angle of jib
Magnetometer	→	c) Magnetic angle	→	Height of hook
Barometers	→	d) Barometric pressure		Heading angle of beam
Gyroscope (IMU)	→	e) Roll, pitch, and yaw angles		Swing motions of beam

Fig. 5. An illustration of the smart mounted to the tower crane

The tower crane was in use on the site of a high-rise residential development project in the New Territories, Hong Kong. The smart cores collected and updated information on the real-time operation conditions of the tower crane and the materials hoisted (i.e. four precast beams) every 3 seconds throughout the operation. This formed a big data set, 1,270 sets of well-structured records, an excerpt of which is shown in Fig. 6.

id	sender_name	time_sender	lat	lng	alt	alt_imu	heading_gps	heading_imu	pitch_imu	roll_imu	temp_imu
12845	c1027	2016-11-07 14:07:52	22.414655	113.97579	10.2	37.78452	150	-103.71865	0	-1.10171	41.4
12846	c1027	2016-11-07 14:07:52	22.414655	113.97579	10.2	37.61805	150	-101.14362	0	-2.1858	41.4
12847	c1027	2016-11-07 14:07:52	22.414655	113.97579	10.2	41.79813	150	-102.55789	0	-1.76239	41.3
12848	c1027	2016-11-07 14:08:10	22.414653	113.975793	10.5	43.5526	9.2	-102.5936	0.21869	-1.74893	41.2
12849	c1027	2016-11-07 14:08:12	22.414657	113.975792	10.4	48.31926	99.1	-102.92745	-0.44073	-1.76234	41.1
12850	c1027	2016-11-07 14:08:12	22.414657	113.975792	10.4	45.97821	99.1	-103.11963	-0.65854	-1.31683	41.1
12851	c1027	2016-11-07 14:08:12	22.414657	113.975792	10.4	44.47211	99.1	-102.20269	-0.43904	-2.41327	41.1
12852	c1027	2016-11-07 14:08:12	22.414657	113.975792	10.4	43.46805	99.1	-103.15113	-0.21952	-1.09748	41.2
12853	c1027	2016-11-07 14:08:12	22.414657	113.975792	10.4	39.79	99.1	-102.55152	0.44243	-1.54811	41.3
12854	c1027	2016-11-07 14:08:33	22.41468	113.975772	10.3	34.61115	285.7	-102.44339	0	-1.74895	41.4
12855	c1027	2016-11-07 14:08:37	22.41468	113.97577	10.7	29.09936	58.6	-103.28233	0	-0.43904	41.6
12856	c1027	2016-11-07 14:08:42	22.414672	113.975773	11.2	44.05463	214.8	-111.27988	0.22294	-1.11456	41.2
12857	c1027	2016-11-07 14:08:46	22.414665	113.975773	11.9	45.0587	41.7	-104.54216	0	-1.77604	41.1
12858	c1027	2016-11-07 14:08:50	22.41466	113.975775	12.3	42.46663	219.3	-105.4126	0.22037	-1.76238	41.2

Fig. 6. Sample data captured by the smart cores

A smart management platform (SMP) (c.f. Fig. 3) was developed to visualize the operations and the conditions of the smart tower crane in a real-time manner. As shown in Fig. 7, the SMP has a graphic user interface (GUI). The background is a cyber construction site reproduced from the real site using a WebGL engine Cesium and Microsoft Bing Map. The building information model was obtained and reproduced in the cyber system. A 3D tower crane model was created as the "cyber twin" of the target crane positioned properly on the site to illustrate the real-time operations of the crane. Based on the live data returned by the smart cores, the SMP could reproduce and visualize the motions of the target tower crane simultaneously, with additional aerial and front views for easier perception.

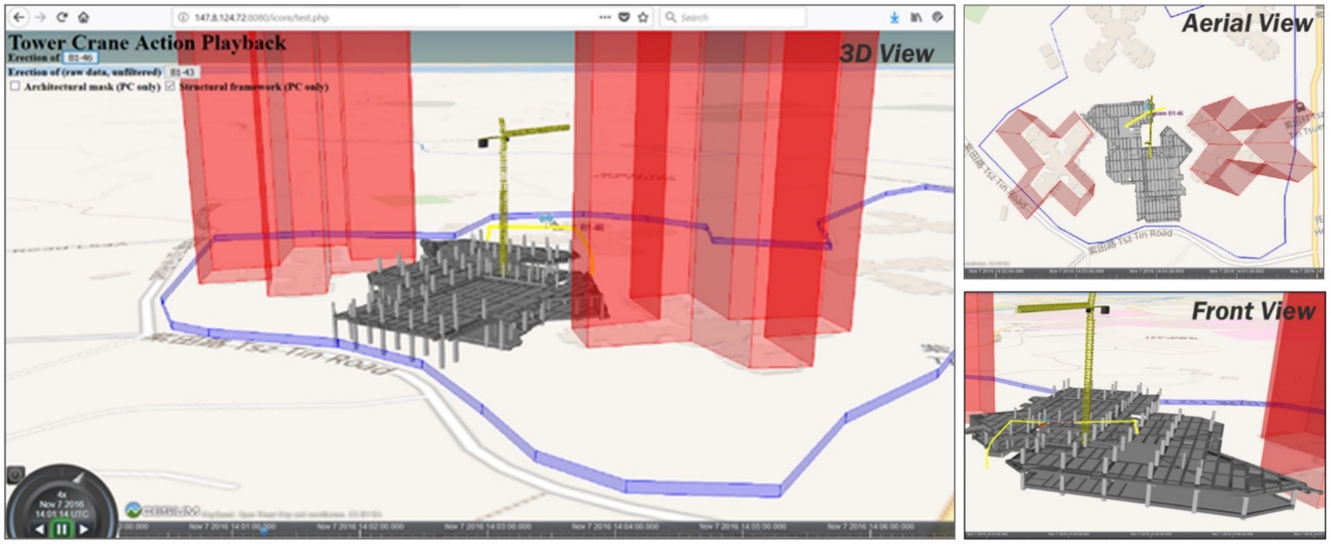


Fig. 7. The smart management platform (SMP) for tower crane safety management

In parallel with the cyber tower crane operation is a visualisation of the big data transmitted back from the smart cores. Fig. 8 illustrates the visualized dataset for the field test. To remap the status of the crane and to identify the dangerous situation, a finite-state machine (FSM) model, with the six states idling, hoisting, slewing, hovering, installation, and resetting, was developed. The change from one status to another required one (or more) speed (or angular speed or velocity) surpassing the threshold(s) pre-defined. For example, the state changed from "idling" to "hosting" at second 8 (S8) when hook velocity > 0.2 m/s. Some state changes are not directly reversible. For example, after changing to "hoisting," the state remained during s16~s24 even though the hook had stopped elevating (see Figure 8). The detections of dangerous situations were also based on the velocities or angular speeds. For example, the criterion of identifying unbalanced hoisting was *jib angular speed* > 0.3°/s, *trolley speed* > 0.15 m/s, and *hook speed* > 0.2 m/s simultaneously. During the installation of beam B1-46 (14:00:07 to 14:07:11, 7 November 2016), the two dangerous situations of unbalanced hoisting and load crossing dynamic restricted zone were sensed and alerts were sent directly to the on-site operator and site manager via text SMS. When referring the identified status of crane and dangerous situations back to Fig. 8, users can observe the events with a highlighted focus. The parallel records of jib, trolley, and hook motions, and the heading direction and swing angle of the beam, can reveal to a safety manager the exact motions of both the crane and the beam.

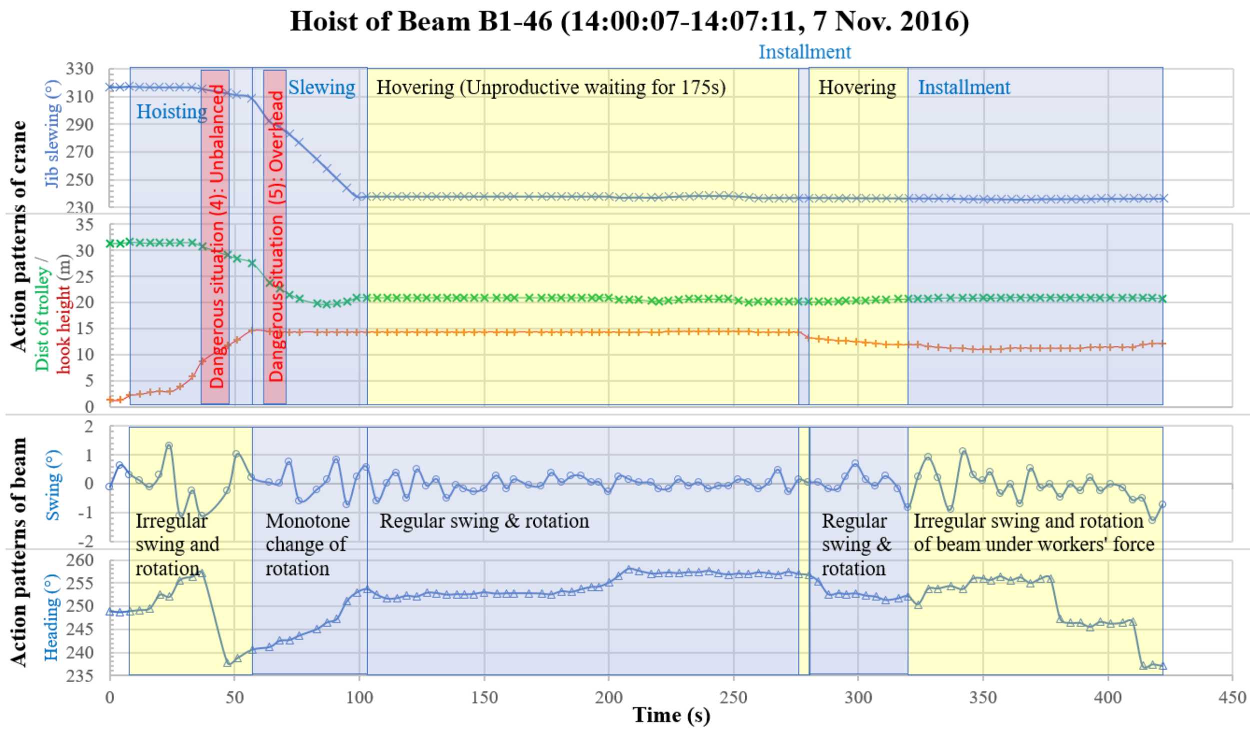


Fig. 8. Visualized action patterns and alerts of dangerous situations

5.3 Lab test

While passive autonomy was successfully achieved in the field test, the exercise of active autonomy, such as execution of a halt action, was untested. After several rounds of negotiation with the cooperating construction company, the active autonomous control was still perceived as non-compliant with existing codes of practice (Irani and Kamal, 2014). Hence, a further test was conducted in a controlled lab environment to demonstrate and validate the feasibility of active autonomy. A model tower crane capable of emulating actual tower crane movement was assembled with LEGO®. A servo motor was used to control its movements both clockwise and anti-clockwise and at different speeds. The same smart core used in the field test was attached to the main jib of the model tower crane to control its motions so as to prevent dangerous situations developing into accidents.

The lab test focused on one specific dangerous situation identified in the field test: the jib crossing a restricted area. The restricted area is for on-foot workers to safely work within or passers-by to walk through. In the lab test, if the jib of the smart tower crane moved into the buffer range of the restricted area, the smart tower crane was to autonomously halt the operation. A cyber 3D tower crane was developed in an online monitoring interface and linked to the LEGO® tower crane to visualize the crane motion in real-time. The restricted area pre-determined in the LEGO® model was also converted to the online monitoring interface at the same scale. The LEGO tower crane was initially set out of the restricted area and moved steadily towards the restricted area (Fig. 9a). When the jib was out of the restricted area, it operated normally with no alert triggered. On touching the buffer range at one side of the restricted area, the policy awareness of the smart core diagnosed the condition as a dangerous situation, triggering the amber alert in the SMP (Fig. 9b). When the jib was entirely within the buffer range, the alert was continuously triggered as the dangerous situation was not resolved. When the jib touched the boundary of the restricted area when swinging across the buffer range, the smart core instantly reacted by pausing the motor, stopping the jib motion (Fig. 9c), and a red alert was triggered.

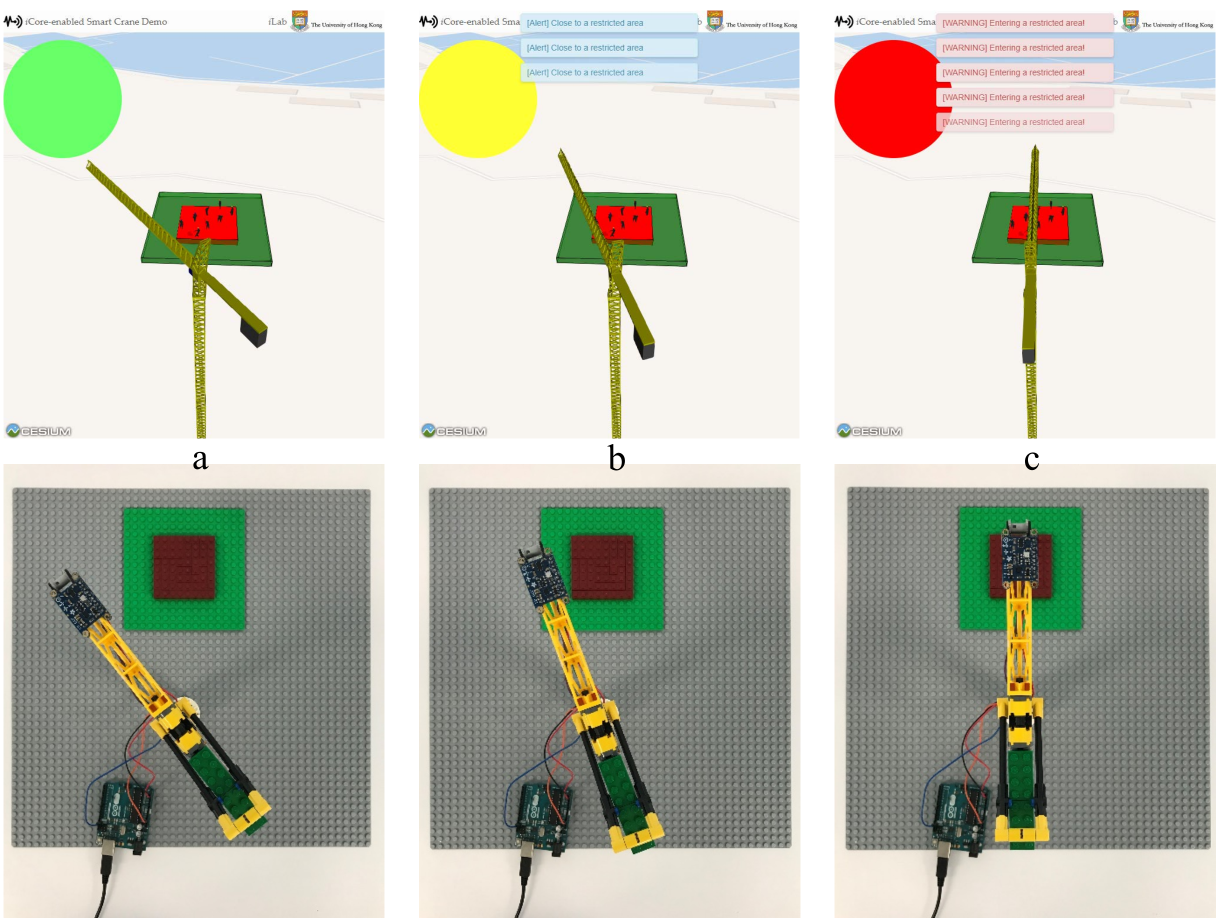


Fig. 9 The active autonomy lab test for the SCO-enabled OHS management system

In order to test the precision of the halt reaction, the rotation angles sensed by the smart core were compared with the actual rotation angles. These were obtained by a rotary sensor tied to the motor throughout the whole process. The degree of difference was measured using the root mean squared error (RMSE) as shown in Equation (1).

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Actual_i - Measured_i)^2} \quad (1)$$

Data from the gyroscope, accelerometer and the magnetometer were fused through the Kalman filter. Based on 87 sets of data, the value of RMSE was 1.76 degree, indicating that the reaction of the smart tower crane was ±1.76 degree ahead of or lagging the movement of the jib; acceptable in the controlled lab environment. The lab test supplements the field test by demonstrating the automatic control potential of SCOs. If improper operation is yet to be manually stopped, the smart core can autonomously control the dangerous condition, thus preventing it from developing into a serious accident.

6. Discussion

SCOs, with their core smart properties of awareness, communicativeness, and autonomy, present a new opportunity to improve OHS management in the construction industry. Compared with traditional OHS management systems that collect and analyse after-accident data, the SCO-enabled OHS management system inherits several advantageous functions from existing proactive technologies (Fang *et al* 2016, Teizer *et al.* 2010, Yang *et al.* 2010) such as worksite monitoring, hazard detection, alerting, and data visualization. Unlike those of traditional OHS management systems, these functions offer round-the-clock monitoring and objective record taking. Another important distinguishing feature of the SCO-enabled OHS management system is its autonomy. The system has potential to prevent dangerous situations from developing into fatal accidents by taking active and prompt actions in conditions that would overload human thinking and reacting abilities. Existing studies on construction OHS management have investigated just one or two specific SCO properties, such as policy awareness empowered by a ranged-based sensors network, or passive autonomy for issuing alerts. This study, however, has shown that the panoramic and interconnected smart properties of SCOs can not only objectively identify the dangerous situations but also deal with them promptly.

Several innovations are offered by this study. Firstly, SCOs present a new way to integrate in a single management system with the monitoring, identification, and visualization of dangerous situations, as well as alerting and autonomous action-taking functions. Although its architecture is multi-layered and its operation processes may seem complicated, the SCO-enabled OHS management system can be encapsulated into one or more smart cores and executed instantly using their computational power. The smart core has customizable functions, and it can be mounted to and demounted from existing construction objects. Secondly, this approach aims not to alter existing functionalities of construction objects, but to make them smarter with the introduction of SCOs. This can be achieved with minimal interference with existing construction processes. There are plenty of cases where researchers or consultants have introduced new, grand smart systems, which have proven futile due to requirements placed upon construction personnel to cater these systems (Woudhuysen and Abley 2004). The system proposed in this paper aligns with the argument that a successful smart construction system is the one that causes the least interruption to accepted processes (Niu *et al*. 2016). The automotive industry provides a parallel example with its successful implementation of smart systems in vehicles.

This study has begun the work of introducing data mining, pattern recognition, machine learning, and artificial intelligence (AI) to construction OHS management. By mining the large amounts of relevant data collected, AI can be developed. Too often in construction, data is scattered across systems (Cheng and Teizer 2013). Deviations among emerging technologies make data consolidation difficult, limiting their potential to provide substantive information, which can support smarter decision making. The SCO-enabled OHS management system integrates various data/information islands in the same platform and makes good use of big data. These data collected can be further analysed for worker behaviour patterns, which could in turn contribute to safety training, and endeavours fostering a safety culture and climate.

It may be claimed that the smart system proposed here is too ambitious and impractical, especially given that the construction industry has long been regarded a notorious “laggard” in technology development and adoption (Liu et al. 2018). In developing an SCO-enabled smart system, the intention is not to persuade construction industry personnel to relinquish the existing protections offered by PPE and the safety climate they have cultivated. Rather, the system is intended to provide an extra layer of protection where existing protections fail. Finding a balance between traditional fragmented management and "full AI" that supersedes human beings is a delicate matter. What this study proposes, however, is a "narrow AI" that equals or exceeds human intelligence for certain tasks.

While this research provides an innovative, operable system to enhance OHS management by focusing on dealing with the dangerous situations, readers are reminded that it does not aim to introduce a technical solution *per se*. Rather, it aims to promote an ideological shift. An essential purpose of this paper is to urge researchers and practitioners to go beyond the improvements offered by the traditional first and second waves of construction OHS management to explore AI as the third wave. Although the AI provided by SCOs is rudimentary, this should not prevent us from devoting greater efforts to this promising area. Dating back to twenty years ago, the accident-avoiding car with the intelligent cruise control system is envisioned less realistically as a grand development direction of AI in Reddy's (1996) work. Despite continuing scepticism regarding the development of AI, the introduction of autopilot cars to the market has proven that smart systems are by no means mere fantasy.

The fact that the autonomy of the smart system could only be tested in a lab environment is not considered by the authors to be a limitation of this study. On the contrary, it vividly reveals the difficulties and resistance AI would encounter in the practical world of construction, and encourages us to devise robust AI solutions as a means of convincing practitioners. Solutions to technological hurdles such as scalability, endurance, and replacement of smart systems should be investigated and tested rigorously, particularly in the case of systems designed to manage the safety and health of workers. When in the future AI reaches technical maturity, bigger challenges may lie ahead in navigating codes of practice, cultural norms, and ethical concerns. Now, however, is the moment to explore AI to achieve smarter and safer construction.

7. Conclusions

This research offers an in-depth exploration of smart construction objects (SCOs) focusing on their smart abilities in construction occupation health and safety (OHS) management. Deviating from traditional research on OHS management using safety technologies or developing a safety culture, this research argues for artificial intelligence (AI) in improving the stagnant OHS management in construction. By augmenting existing construction resources with core smart properties including awareness, autonomy, and communicativeness, SCOs represent an integrated means of monitoring, visualizing, alerting, and action taking in the management of dangerous situations. Targeting the operation of a tower crane, the SCO-enabled OHS management framework and system were validated in a lab experiment. The results of this experiment demonstrate the feasibility of applying the proposed system to on-site practice.

The research makes several practical and theoretical contributions. Firstly, by referring to the example in this research, the SCO-enabled OHS management framework can be extended and applied to other smart technology-enabled OHS management systems to develop management strategies. The multilayer architecture of the system developed in this study provides clear direction and sufficient detail for other researchers interested in replicating this work. Theoretically, while acknowledging the merits of traditional PPE and human-based OHS management strategies, this research seeks a united front on smart technology-enabled OHS management systems by drawing attention to the deficiencies of traditional strategies, specifically in provision of proactive monitoring and real-time alerts. Beyond the monitoring and alerting functions supported by existing OHS management systems, this research argues for SCO autonomy as a new dimension which can prevent dangerous situations from becoming fatal accidents in a timely manner. When proposing the AI-based solution as the direction of the "third wave" of construction OHS management, this study aims to emphasize the differences and potential values that could be brought about by SCOs. This study not only provides a sound theoretical foundation for efforts to proactively manage dangerous situations, but also concludes that future research efforts should be devoted to the achievement of smarter construction, incorporating AI in particular, to reduce major accidents. By exploring the AI offered by SCOs, there are opportunities and challenges in steering the construction industry toward a smarter and safer future.

References

Abdelhamid, T. S., and Everett, J. G. (2000). Identifying root causes of construction accidents. *Journal of Construction Engineering and Management*, 126(1), 52-60.

Cambraia, F. B., Saurin, T. A., and Formoso, C. T. (2010). Identification, analysis and dissemination of information on near misses: A case study in the construction industry. *Safety Science*, 48(1), 91-99.

Cheng, T., and 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.

Chi, S. and Han, S. (2013). Analyses of systems theory for construction accident prevention with specific reference to OSHA accident reports. *International Journal of Project Management*, *31*(7), 1027-1041.

Choudhry, R. M., and Fang, D. (2008). Why operatives engage in unsafe work behavior: Investigating factors on construction sites. *Safety Science*, *46*(4), 566-584.

DeJoy, D. M. (1990). Toward a comprehensive human factors model of workplace accident causation. *Professional Safety*, 35(5), 11.

Fang, D., Jiang, Z., Zhang, M., and Wang, H. (2015). An experimental method to study the effect of fatigue on construction workers' safety performance. *Safety Science*, 73, 80-91.

Fang, Y., Cho, Y. K., and Chen, J. (2016). A framework for real-time pro-active safety assistance for mobile crane lifting operations. *Automation in Construction*, *72*, 367-379.

Fitton, D., Sundramoorthy, V., Kortuem, G., Brown, J., Efstratiou, C., Finney, J., and Davies, N. (2008). Exploring the design of pay-per-use objects in the construction domain. In *European Conference on Smart Sensing and Context* (pp. 192-205). Springer Berlin Heidelberg.

Flanagan, R., Jewell, C., Lu, W., and Pekericli, K. (2014). *Auto-ID — Bridging the Physical and the Digital on Construction Projects.* Chartered Institute of Building.

Green, L., and Tominack, G. (2012). Real-time proactive safety in construction. *Power*, 156(1), 62-65.

Hadikusumo, B. H. W., and Rowlinson, S. (2002). Integration of virtually real construction model and design-for-safety-process database. *Automation in Construction*, 11(5), 501-509.

Hahn, S. E., and Murphy, L. R. (2008). A short scale for measuring safety climate. *Safety Science*, 46(7), 1047-1066.

Harris, M. (2015). Documents confirm Apple is building self-driving car. *The Guardian*, *14*.

Heinrich, H. W. (1941). *Industrial Accident Prevention. A Scientific Approach.* (Second Edition).

Hinze, J., Hallowell, M., and Baud, K. (2013). Construction-safety best practices and relationships to safety performance. *Journal of Construction Engineering and Management*, 139(10), 04013006.

Holt, A. S. J. (2008). *Principles of construction safety*. John Wiley and Sons.

International Labour Office (ILO), 2001. *Guidelines on Occupational Safety and Health Management Systems.* MEOSH/2001/2(Rev.). International Labour Office, Geneva.

Irani, Z., and Kamal, M. M. (2014). Intelligent systems research in the construction industry. *Expert Systems with Applications*, *41*(4), 934-950.

Kessler, A. M. (2015). Elon Musk Says Self-Driving Tesla Cars Will Be in the US by Summer. *The New York Times*, B1.

Kurzweil, R. (2005). *The singularity is near: When humans transcend biology*. Penguin.

Lu, W., Huang, G. Q., and Li, H. (2011). Scenarios for applying RFID technology in construction project management. *Automation in Construction*, 20(2), 101-106.

Mohamed, S. (2003). Scorecard approach to benchmarking organizational safety culture in construction. *Journal of Construction Engineering and Management*, 129(1), 80-88.

National Safety Council. (2015*). Injury Facts®,* 2015 Edition*.*

Neitzel, R. L., Seixas, N. S., and Ren, K. K. (2001). A review of crane safety in the construction industry. *Applied Occupational and Environmental Hygiene*, *16*(12), 1106-1117.

Niu, Y., Lu, W., Chen, K., Huang, G. G., and Anumba, C. (2015). Smart construction objects. *Journal of Computing in Civil Engineering*, 30(4), 04015070.

Niu, Y., Lu, W., Liu, D., Chen, K., Anumba, C., and Huang, G. G. (2016). An SCO-Enabled Logistics and Supply Chain–Management System in Construction. *Journal of Construction Engineering and Management*, 04016103.

OSHA Directorate of Training and Education. (2011a). *Construction Focus Four: Caught-In or -Between Hazards,* OHSA Training Institute.

OSHA Directorate of Training and Education. (2011b). *Construction Focus Four: Electrocution Hazards,* OHSA Training Institute.

OSHA Directorate of Training and Education. (2011c). *Construction Focus Four: Fall Hazards,* OHSA Training Institute.

OSHA Directorate of Training and Education. (2011d). *Construction Focus Four: Struck-by Hazards,* OHSA Training Institute.

Pearce, D.W. (2003), Environment and business: socially responsible but privately profitable? In J. Hirst (ed). *The Challenge of Change: Fifty Years of Business Economics*, 54-65, London: Profile Books.

Petersen, D. (1984). *Human-error reduction and safety management*. STPM Press, New York.

Raheem, A. A., and Hinze, J. W. (2014). "Disparity between construction safety standards: A global analysis." *Safety Science*, 70, 276-287.

Raviv, G., and Shapira, A. (2018). Systematic approach to crane-related near-miss analysis in the construction industry. *International Journal of Construction Management*, 18(4), 310-310.

Reason, J. (2000). Human error: models and management. *BMJ*, 320(7237), 768-770.

Reddy, R. (1996). The challenge of artificial intelligence. *Computer*, 29(10), 86-98.

Shapira, A., and Lyachin, B. (2009). Identification and analysis of factors affecting safety on construction sites with tower cranes. *Journal of Construction Engineering and Management*, *135*(1), 24-33.

Shepherd, G.W., Kahlera, R.J., Cross, J., 2000. Crane fatalities – a taxonomic analysis. *Safety Science* 36 (2), 83–93.

Simon, H. A. (1976). *Administrative behavior*, 3rd Edition. Free Press, New York.

Somavia, J. (2005). Facts on safety at work. *International Labor Office (ILO), Technical Report*.

Sterman, J. D. (1989). Modeling managerial behavior: Misperceptions of feedback in a dynamic decision making experiment. *Management Science*, 35(3), 321-339.

Teizer, J., Allread, B. S., Fullerton, C. E., and Hinze, J. (2010). Autonomous pro-active real-time construction worker and equipment operator proximity safety alert system. *Automation in Construction*, 19(5), 630-640.

Tsang, Y. T., Fung, I. W., Tam, V. W., Sing, C. P., and Lu, C. T. (2017). Development of an accident modelling in the Hong Kong construction industry. *International Journal of Construction Management*, 17(2), 124-131.

Woudhuysen, J., and Abley, I. (2004). *Why is construction so backward?* Wiley Academy.

Wu, W., Gibb, A. G., and Li, Q. (2010). Accident precursors and near misses on construction sites: An investigative tool to derive information from accident databases. *Safety science*, 48(7), 845-858.

Yang, H., Chew, D. A., Wu, W., Zhou, Z., and Li, Q. (2012). Design and implementation of an identification system in construction site safety for proactive accident prevention. *Accident Analysis and Prevention*, 48, 193-203.

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