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Visualization technology-based construction safety management: A review

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Abstract: Construction safety management has been a popular issue in research and practice in recent years due to the high accident and death rates in the construction industry. The complexity and variability of construction sites makes safety management more difficult to implement than in other industries. As a promising technology, visualization has been extensively explored to aid construction safety management. However, a comprehensive critical review of the visualization technology in construction safety management is absent in the literature.

This paper provides a comprehensive review to investigate research and development, application methods, achievements and barriers to the use of visualization technology in safety management, and suggests possible future research directions to extend its application. To achieve this, 78 relevant papers from 2000 to 2015 are reviewed. It is found that visualization technology can improve safety management by aiding safety training, job hazard area (JHA) identification and on-site safety monitoring and warnings, but there are barriers or limitations involved. Existing location technologies, for instance, can perform well only in relatively small areas due to their generally poor penetrating performance. Finally, possible future research directions are proposed to benefit the extensive application of visualization technology for construction safety management in both theory and practice.

Keywords: Construction, safety management, visualization technology, review.

1. Introduction

Construction has become one of the most dangerous industries due to the harsh work environment and high risks involved [1]. In China alone, there was an average of more than 2500 annual accident deaths accompanied by serious safety accidents in the construction industry from 1997 to 2014 (see Fig. 1)[2]. In addition to developing countries, the construction industry is also recognized as dangerous in developed countries such as U.S. and U.K. [3]. According to global statistical data, its accident death and injury rate is three and two times higher respectively than the average of other industries [4]. In spite of more attention being paid to safety management in recent years, the accident rate of the construction industry continues to be high [5].

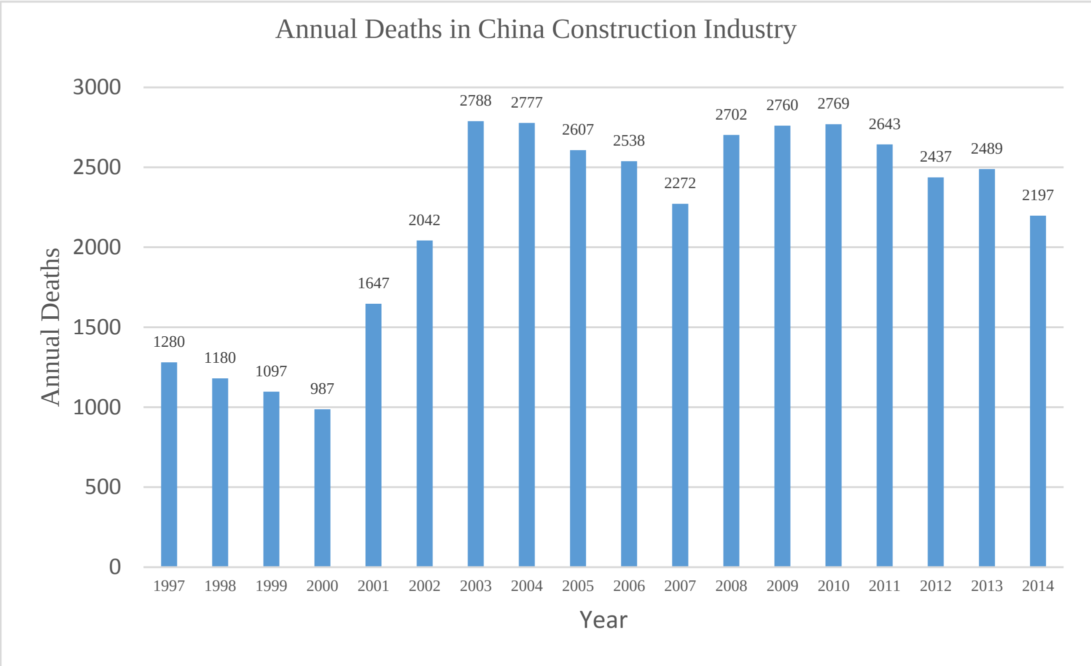

Fig. 1. Annual deaths in the China construction industry from 1997 to 2014

Construction safety management can be divided into the pre-construction stage and construction stage[6]. In pre-construction, potential safety hazards are normally identified based on the safety officers' or project managers' experience and eliminated via safety training and safety planning. During construction, accidents are prevented by monitoring workers and the environment on site [7]. However, some problems still exist in construction safety management, summarized as follows (see Fig. 2):

- *Insufficient safety training*. Safety training is regarded as a useful safety management method [8], but is traditionally based on indoor teaching, which lacks interaction, intuition and hands-on training, and therefore does little improve the safety consciousness of workers [9].
- *Incomplete safety planning*. Failing to identify safety hazards is a major cause of construction accidents [10] and the identification of a job hazard area (JHA) can significantly improve safety and decrease associated costs [11,12]. Traditionally, safety planning is based on a team meeting [13] in which JHAs are identified by imagining construction processes with the aid of 2D drawings, schedules, safety rules and experience, but lacking an intuitive method of representing the construction process. A large number of JHAs also go undetected because of the uniqueness, dynamism and complexity of the construction environment.
- *Invalid site monitoring*. Site monitoring is currently the key to safety management [9]. Safety officers often use a checklist to manage construction safety by identifying and recording violations [14]. In the absence of technological support, however, it is impractical to monitor the whole of sites at once in this way due to their large size and dynamic environment [15].

The above problems derive from the information level. Fig. 2 shows the features of construction information, which is abstract, dynamic and massive. These features of construction information impede construction training, planning and monitoring, since workers and safety officers have to imagine what the construction site would be like according to construction drawings and documents, which are not intuitional and efficient enough.

Current research is making some efforts to solve these problems with the help of visualization technology, which not only makes information digital and visual, but also depicts the construction environment and processes comprehensively and accurately. The main contributions of visualization technology to safety management can be summarized as (Fig. 2):

- *Improving the safety training of workers*. Revealing the visual construction process and site environment can improve the safety consciousness of workers so they more easily understand safety management-related knowledge and the potential safety problems involved [16,17].
- *Aiding JHA identification and management*. A visual and virtual construction site can aid project managers or safety officers in identifying JHAs automatically or manually prior to commencing construction, therefore benefiting safety planning [18].
- *Aiding on-site safety monitoring*. Due to the integration of site information storage media, visualization technology can improve efficiency and effectiveness of safety management by assisting safety officers in monitoring the unsafe behaviors of workers and construction equipment in real time [19].

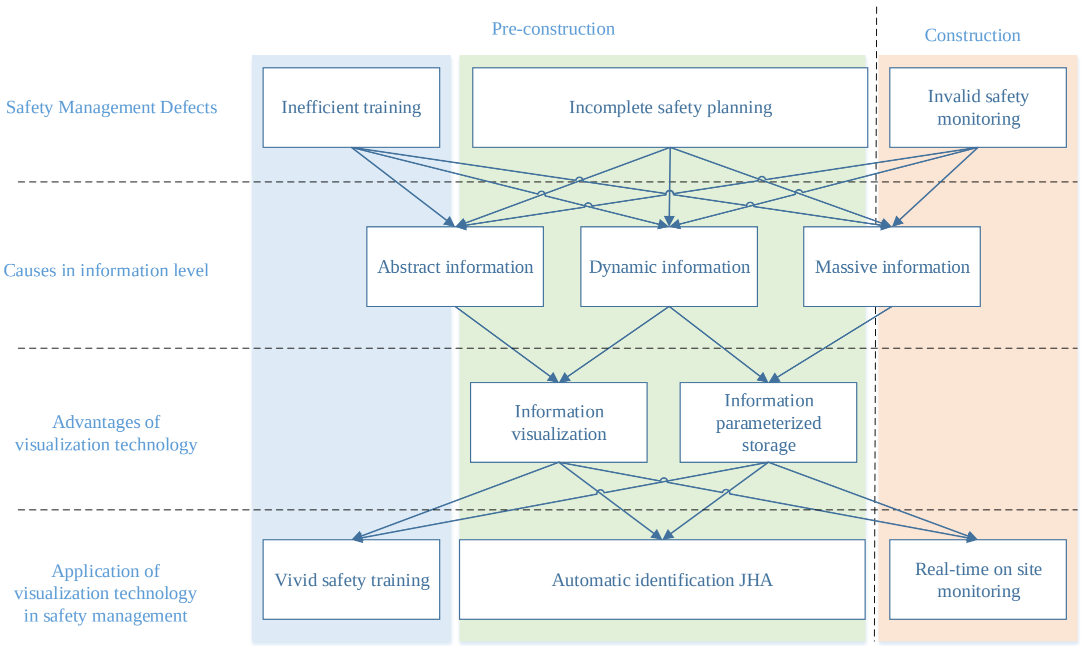

Fig. 2. Visualization technology-aided construction safety management.

Though visualization technology has been regarded as a promising approach to improving construction safety management, there has not yet been any systematic review to clarify what is currently available or what the future might hold. This paper, therefore, provides such a review to investigate research and development, application methods, achievements and barriers, and suggest possible future research directions. In the following sections, key relevant research is firstly identified, then visualization technology-aided safety management is reviewed from pre-construction and construction perspectives, and the gap between current research and practical requirements is identified.

2. Research method

According to Heinrich's safety theory, the cause of accidents involves unsafe objects and worker behaviors [20], while safety management involves worker safety training, the identification and management of JHAs during pre-construction and the monitoring of workers and construction equipment during the construction process [19,21]. In identifying the key research relating to the use of visualization technology, this paper provides a review in terms of these four aspects.

2.1 Literature search

As Zhou et al. [22] allude, visualization technology involves BIM (Building Information Modeling), 4D CAD (Four-Dimensional Computer Aided Design), VP (Virtual Prototyping), VC (Virtual Construction), VR (Virtual Reality) and AR (Augmented Reality). BIM may be regarded as a visual database, integrating a building's dimensional and attribute information [23] and is often used in the static analysis and comparison of construction processes. 4D CAD, is widely used in construction[16] and provides schedule simulation by adding the schedule to 3D models, VC involves multi-dimensional construction process simulation that takes into account not only 3D (or visual) and schedule information, but construction resources such as workers and equipment. Similar to VC, VP is often used to aid worker safety training [24] by focusing on dynamic changes in schedule, cost, resources, etc. - placing more emphasis on environment simulation to provide people with a feeling of telepresence [25]. Relevant publications were identified by searching the *Web of Science* and *ASCE Library* databases with the following keywords:

(1) Visualization technology: “BIM”, “4D CAD”, “VP”, “VC”, “VR”, “AR” and “information technology”, connected by “or”
(2) Research topic: “construction” and “safe*” (meaning “safe” and its derivatives)
(3) Research field: "science technology" selected in the *Web of Science*
(4) Research direction: "engineering or computer science", "construction building technology", "automation control system", "telecommunication", "urban studies" and "science technology other topics" selected in the *Web of Science*.

2.2 Overview of the literature

The search words helped to identify 78 relevant papers. These are summarized in Fig. 3 in terms of the number of annually publications from 1999 to 2015. The number of different visualization technologies used in these papers (Fig. 4) clearly indicates BIM, 4D and VR to be the most popular.

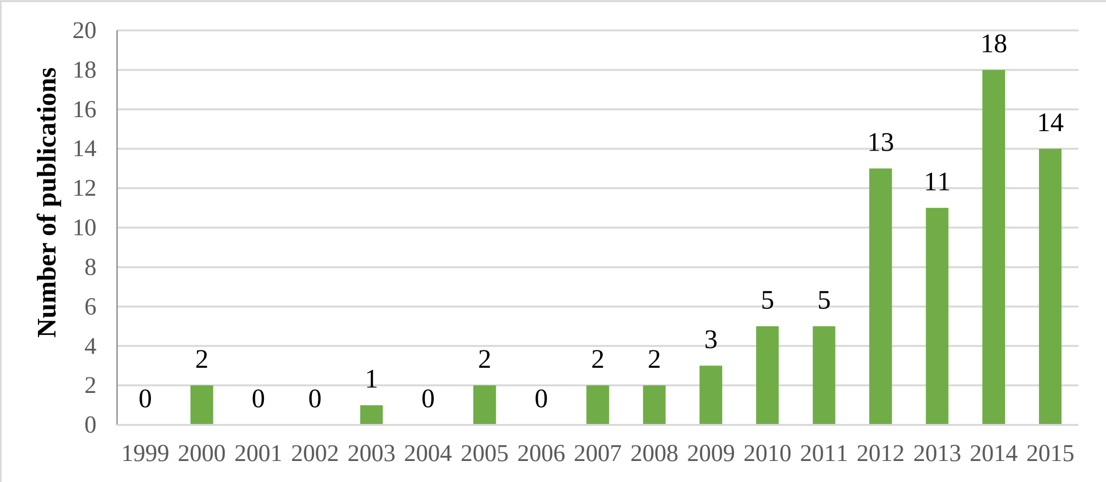

Fig. 3. Number of publications by year

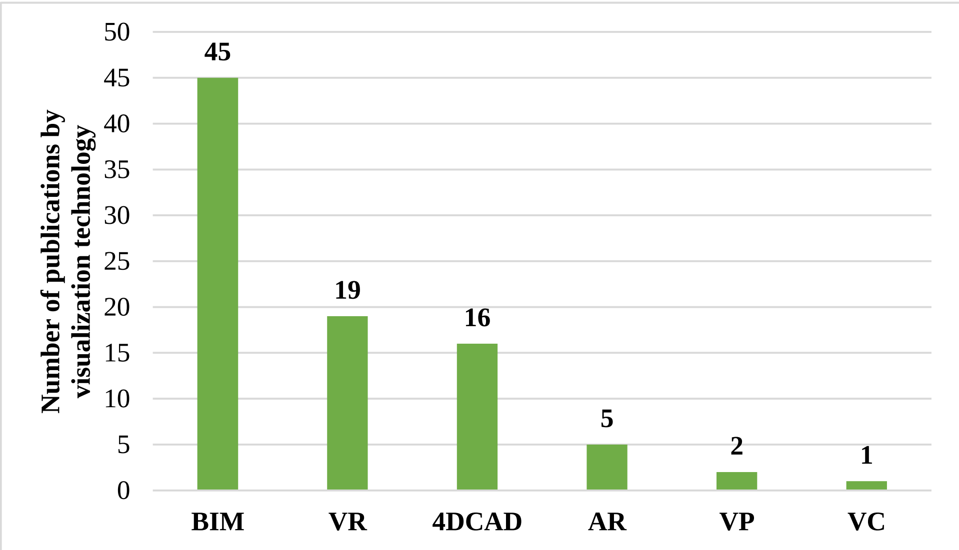

Fig. 4. Number of publications by visualization technology

Fig. 5 shows the number of publications by research topic divided into the five categories of safety training, JHA identification, monitoring worker behavior, monitoring construction environment and early warning on site. Intriguingly, most papers focus on JHA identification before construction. To some extent, this matches the distribution in Fig. 4, with BIM also accounting for the most papers. This is because the application of BIM in safety management mainly focuses on safety planning in the pre-construction stage except for on-site monitoring, which needs real-time information collection and analysis.

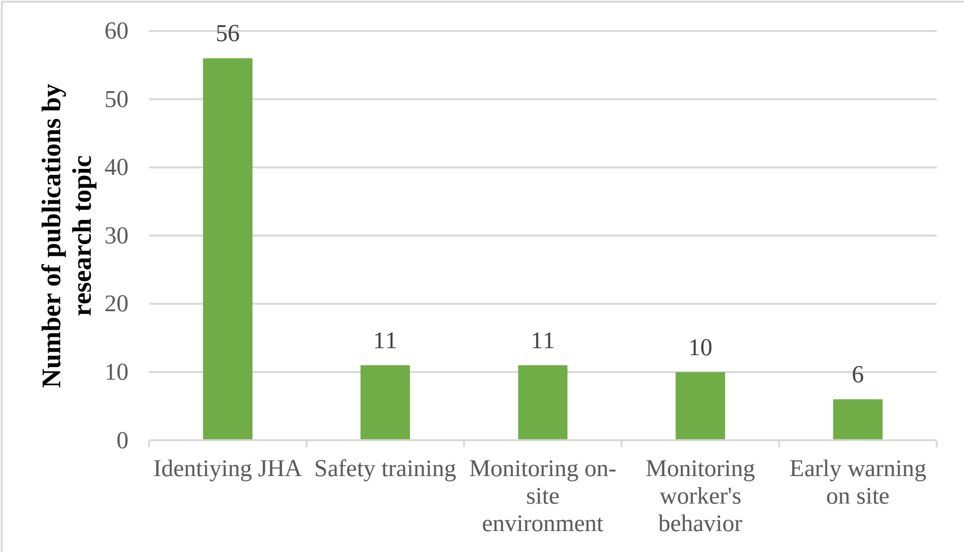

Fig. 5. Number of publications by research topic

3. Visualization technology and safety management during pre-construction

3.1 Safety training

Safety training provides an efficient way of improving safety management [26]. This traditionally comprises on-site training and off-site training. On-site training is inefficient and may interfere with normal construction activities and hence reduce productivity, while off-site training lacks hands-on learning opportunities for workers. Visualization technology can improve safety training by providing visualized information and offering virtual off-site hands-on training.

Visualization technology provides a visual approach to safety training in which construction processes and the environment can be vividly demonstrated in a 3D way. For example, BIM and VR have been adopted to build a virtual and visual construction environment or sites to aid in safety training [27,28]. Workers can easily recognize potential hazards embedded in such a visual environment, thus improving the training. Since safety training usually involves hands-on operations that are difficult to understand using only text or photographs, BIM is also used to visualize hands-on safety operations, making the training easier to understand [29].

Visualization technology integrated with game technology provides an interactive approach to safety training. This allows workers to improve their safety consciousness by interacting with a virtual construction environment and checking potential hazards involving unsafe behaviors, lack of necessary safety facilities, etc. For instance, some interactive safety training systems have been developed by integrating BIM or game technology for potential hazards [30]. Based on such systems, workers can walk through a virtual construction environment, with safety-related prompt messages appearing when they are close to unsafe operations or JHAs. Systems are also often used to evaluate worker safety consciousness based on their own identification of unsafe factors [30,31]. Furthermore, the interactivity of safety training systems has been being improved by enabling workers to control virtual models by mouse, keyboard or hand grip (such as in operating a crane model [17,32]).

Visualization technology provides a cooperative approach for safety training. Many construction accidents are caused by inadequate cooperation among workers or operators and therefore need to be taken into account. Network-based safety training platforms have been built through the integration of BIM and game technology, in which workers are able to carry out their operations in a virtual way using individual computers within the network, and communicating and cooperating with each other in real time [17,33]. In this way, workers can experience the uncertainty of real construction processes and learn how to cooperate with each other before working on site.

In summary therefore, visualization technology combines safety-related project information, presents it in a visual model featuring interaction and cooperation and helps workers have a better understanding of safety knowledge or operations. As this is all realized by computers, the processes and results of the training can be recorded as the basis for safety management on site.

3.2 JHA identification and management

A JHA refers to an area where potential job hazards lie and are usually a source of collision, edges and holes, as well as temporary structures. JHA identification and management is the foundation of safety training and construction site safety management, and in recent years visualization technology is starting to be employed to aid this process.

3.2.1 JHA identification

Visual technology offers a 3D and automatic approach to identifying JHAs on behalf of traditional 2D drawings or documents. For example, 3D building models can be used to assist safety officers in identifying JHAs in safety meetings [13,34]. Although this method improves the performance of JHA identification, it is also an experience-dependent manual process. In order to improve this, safety rules have been developed and integrated with visualization technology [35,36]. JHAs such as holes and edges can be automatically identified by referring to the building element information from 3D models and relevant safety rules [37,38]. As only building information is included in the method, it has been suggested that additional information concerning the site, temporary facilities, equipment, etc., should be integrated to provide the comprehensive identification of JHAs [39,40].

Visual technology provides a simulation approach to identifying JHAs (particularly those involving spatial collisions) by integrating more site information. It is important to detect potential spatial collisions when safety planning as collisions are usually caused by improper construction planning and can be eliminated by modifying construction methods or schedules. Traditionally, it is difficult to identify and eliminate such kind of collisions based solely on relevant 2D drawings and experience. With the aid of visualization technology, the space demands of each activity can be analyzed and spatial collisions identified [41,42]. To do this, a workspace collision detection process with 4D-BIM has been proposed that considers both the time and space of activities, which increases detection accuracy [43]. Construction equipment collisions are also an important issue and collision detection algorithms based on bounding boxes, which cover the boundary of equipment motion, have been developed to detect these by identifying the time and space relationships for each bounding box [44,45].

Building structures and temporary structures are also potential JHAs, as they need to be stable enough to avoid collapse during and after construction. 4D CAD, BIM and structural analysis software have been integrated to simulate and analyze such possible collapses [46-48]. Also, by integrating BIM with oxygen and temperature sensors, dangerous environment information can be identified and highlighted in the virtual model [49].

3.2.2 JHA management

JHA management consists of the assessment and elimination of JHAs and visualization technology provides 3D visual support, such as by representing different risk grades by different colors, which significantly contributes to safety risk management [50], and enabling protection measures to be automatically added to JHAs so as to prevent potential hazardous situations from developing into accidents. For example, BIM and safety rules have been applied to visualize the scaffolding installation process and identify associated potential hazards [51], while safety protection can be automatically provided through the analysis of the time and place of the installation and removal of guardrails and scaffolding [35,52]. However, research to date has realized automatic JHA identification for only a few cases, such as holes, edges and scaffolding.

In summary, therefore, the advantages of using technology for visualizing and integrating information for construction safety management have been demonstrated for the pre-construction stage [53]. In particular, it conveys intuitively understood information that helps workers appreciate the site environment better as well as integrating both project information and safety-related knowledge, and improving construction safety management by identifying, assessing and eliminating JHAs in advance of construction work taking place. The only shortcoming in previous research appears to be the insufficiently comprehensive identification of JHAs. Most studies focus on particular hazard areas such as holes and edges that may lead to a falling accident, but these are only some of the JHAs that exist on site. Applications to other kinds of JHAs, such as those involving electric shocks, have yet to be considered.

4. Visualization technology and safety management in construction

According to Reason's model [54], on-site safety management is the last management layer for preventing accidents and is in need of greater emphasis. Current this relies mainly on safety officer checks, which are very time consuming [55]. Visualization technology solves this problem by integrating and analyzing information concerning worker behavior and the on-site environment with the help of location, imaging and alerting technologies[56,57]. The main aspects of visualization technology-aided construction safety monitoring are: (1) on-site worker behavior monitoring, (2) on-site environment (including equipment) monitoring, and (3) information integration, analysis and early warnings.

4.1 On-site worker behavior monitoring

Unsafe worker behaviors are a major cause of workplace accidents generally [58]. Normally, three kinds of unsafe behaviors are involved on-site: approaching JHAs, misuse of personal protective equipment (PPE) and incorrect operation [19]. Workers approaching JHAs can be identified by monitoring worker locations, while misemploying PPE and incorrect operation can be identified by both location and motion information. On-site worker behavior information, therefore, normally involves location and motion, which can be visualized and analyzed to aid on-site safety management.

4.1.1 Monitoring worker location

Location technology helps in obtaining worker location information. Related research can be divided into two types: sensor-based location and image-based location. *Sensor-based* location calculates the position of an unknown point by measuring the distances between known points to the unknown point. *Image-based* location obtains the coordinates of an unknown point by considering the relative positions between points and a camera.

(1) Sensor-based location

Sensor-based location technologies include Radio Frequency Identification (RFID) , Ultra-wide Band (UWB) , Ultra Sound (US) , Global Position Systems (GPS) , Wireless Local Area Networks (WLAN) , Infrared Radiation (IR) and Chirp Spread Spectrum (CSS) . GPS, UWB and RFID are the three most widely used location techniques.

GPS provides 3D coordinates continually and is insensitive to weather and barriers , and is therefore usually used outdoor to locate and track workers and equipment [59]. UWB can operate both outdoor and indoor, and is also used to locate workers, equipment and materials [60]. It is, however, expensive when used outdoor because of its small signal cover and intensive location network [61] and is therefore more often used indoor [27,61]. By contrast, RFID has a larger signal cover but weaker penetration capability than UWB, thus is often used in outdoor and indoor environments where there are few barriers [62,63]. The different forms of location technologies can also be combined synergistically to improve location performance. Behzadan et al., for example, use a mixed location technology of WLAN indoor and GPS outdoor. This combines the strengths of both techniques but involves the use of more location devices [64].

The ideal location technology on site, therefore, should satisfy the following requirements: (1) a range that is large enough to cover the whole site, (2) sufficiently high accuracy with errors within 1 m [65] and (3) as few devices as possible. There is currently no single location technology that satisfies all these requirements. Due to their generally poor penetrating performance, existing location technologies can perform well only in a relatively small area with few barriers.

(2) Image-based location

Image-based location technologies calculate a worker's 3D coordinates based on the position of two cameras and the relative position between workers and cameras [66,67]. Image-based location technologies do not require workers to carry devices such as tags, but can only locate workers within line of sight and are therefore easily blocked by barriers on site.

In summary, therefore, all the techniques for monitoring worker location can meet only some of the requirements for construction site workers. Image-based location technologies can only locate objects within line of sight and thus would generate a large amount of data to be transmitted and processed if used on the whole site. Sensor-based location technologies need to be combined with each other to realize whole-site location, involving workers carrying more devices that, in turn, may affect their normal site work. The satisfactory whole-site real time location and tracking of workers, therefore, still remains a problem.

4.1.2 Monitoring worker motion

RFID devices have been applied to check for unsafe worker behaviors such as the misuse of PPE [68]. Such behaviors are related to worker motion and are more suited to monitoring by motion-capture technologies. Furthermore, in order to control incorrect operations, real-time monitoring is needed.

Both sensor-based monitoring and image-based monitoring have been proposed. For example, wearable three-axial (vertical, lateral and sagittal) thoracic accelerometers have been developed to capture the motion of workers [69]. However, this device is quite large and may affect normal work. Behzadan et al. have also developed a method to monitor the head gestures and position of crane operators, but which can only be used indoor such as in the cabin of crane [64]. As for image-based motion monitoring, a depth camera is widely used, in which the human skeleton can be extracted from depth pictures. This enables unsafe or unhealthy motions to be identified from the similarity of the captured skeleton to existing samples [70,71]. Although the depth camera method does not involve workers wearing any devices, it is a relatively slow process because of the great amount of data needed and the complexity of the data processing involved.

To summarize, previous research has pointed to ways of monitoring on-site worker behavior theoretically with sensors and cameras, but problems still exist in practice. Sensor-based technology needs extra devices installed on site or worn by workers, which may interfere with normal construction activity and reduce productivity. In addition, barriers and other signals usually interfere with data transmission between sensors and processors. While image-based technology does not involve wearable devices, it is relatively slow and can be used only with workers within line of sight.

4.2 Environment monitoring on site

Visualization technology has been used to aid in monitoring both static and dynamic construction environments, where *static* environment elements are of constant position, such as scaffolding and building structures, while *dynamic* environment elements mainly refer to construction equipment.

4.2.1 Monitoring static environments

The traditional site safety management method is the safety officer’s daily checklist [55], which is neither sufficiently timely nor accurate. Real-time visual simulation can help to solve this problem. Existing methods available include manual simulation, semi-automatic simulation and automatic simulation.

Manual simulation uses electronic methods, such as scanning QR code (Quick Response code) [72], to record safety inspection information instead of by paper documents, but is still carried out manually by safety officers. *Semi-automatic methods* update the site 4D model daily [16], which is also a relatively slow process. *Automatic methods* obtain real-time information by images or other means and are much quicker. An Unmanned Aerial Vehicle (UAV) or Laser Scan shoot sites and capture site information by identifying feature points or lines in photographs [18,73,74]. However, this method involves a time lag due to the large number of points to be transmitted and analyzed. To solve this problem, a smart scanning method has been proposed that scans dynamic objects in real time and thus considerably decreases the number of points needed

[75]. Although these automatic simulation methods are quite efficient and accurate, the output model is only a shell – containing none of the parameters or attribute information necessary for the automatic identification of unsafe factors. Moreover, image-based technologies can operate only within line of sight, so it is difficult to build a parameterized model of the whole site with only one device. Thus on-site static environment information retrieval is still limited.

4.2.2 Monitoring dynamic environments (equipment)

The position and posture of construction equipment change many times during construction work, which makes it difficult to monitor equipment on site. Visualization technology has been employed to solve this by integrating sensor and laser scan technologies.

Sensors are usually employed to obtain the position information of equipment. For outdoor equipment, GPS and other outdoor location technologies can be applied to monitor position. For example, RFID has been used to monitor the distance between individual equipment to possible collisions [76] and UWB has been adopted to track equipment location [61]. However, equipment changes not only in position, but also in posture [77]. Angular and linear displacement sensors have been applied to track the posture of a crane because its motion has a low degree of freedom (DOF) and can be described by parameters such as the altitude of hung objects, rotation angle and length of lifting arm [65,78,79]. The data can be transmitted to a BIM model, which provides the crane operator or safety officer with real-time equipment status.

Laser scanners are also used to build equipment models from a point cloud [77], but again require high-speed data transmission due to the large number of scanned points [75] and a shell model lacking the necessary information for safety management on site.

In short, while sensors can monitor the position and posture of equipment more timely and accurately, image-based technologies can monitor both static and dynamic environment factors without the need to install any sensors.

4.3 Early warnings on site

Visualization technology improves safety management performance in construction by integrating and analyzing real-time worker behaviors and the environment. For safety officers, a virtual model represents the real-time status of a construction site and greatly helps safety supervision. For example, risks can be graded automatically and represented by different colors in the model [80]. For equipment operators, visualization technology offers information concerning the surrounding environment to avoid accidents caused by blind angles [79]. For site workers, early warning signals, such as by vibration and sound, can be sent to avoid accidents. For instance, by calculating the distance between workers and JHAs, it can be automatically judged if workers are in a JHA [21]. Behzadan and Kamat have also proposed a new way of preventing workers from approaching JHAs by equipping them with augmented-reality (AR) glasses to clearly see JHA boundaries [81]. This solves the problem of the time lag involved in sending and receiving traditional warning signals, but the AR glasses are too big and cumbersome to be worn during normal operations.

In summary, visualization technologies involving the integration of information concerning worker behavior and site environments facilitate on-site JHA management and worker unsafe behavior management and prevent accidents by presenting or sending early warning messages.

Research to date into unsafe behavior warnings, however, has focused mainly on location-based warnings and less attention has been paid to motion-based warnings.

5. Discussion and future research directions

Visualization technology has been used to assist in construction safety management by integrating and visualizing construction information. Table 1 summarizes the achievements and shortcomings of the published research to date. A detailed discussion follows, together with some suggestions for future research directions.

5.1 Discussion

5.1.1 Visualization technology-aided safety training

As Table 1 shows, visualization technology facilitates safety training in a visual, interactive and cooperative way. However, existing research mainly develops or customizes specific approaches or platforms for one or some aspects of safety training, such as construction equipment operations [16,73] and prefabricated construction [31], and lacks a comprehensive safety training approach or platform. This leads to high training costs as well as low efficiency. Although some studies propose general safety training approaches [13,27], most focus mainly on the benefits of visualization, with less consideration for interaction and cooperation. Thus, the commonly used visual safety training approach in practice demonstrates unsafe components or activities in only a visual way.

5.1.2 Visualization technology-aided JHA identification and management

Visualization technology has been used to identify and manage JHAs involving major types of accidents, for example that of falling from height [38,82] and those resulting from structural collapse [47] or spatial collisions [41,42] (see Table 1). Some safety rules have been developed to automate hazard identification and prevention, but existing research considers only a subset of accidents that occur, such as those related to temporary holes and edges. Automatic identification is also still in need of efficient and effective implementation. Consequently, potential approaches are not yet widely employed in the construction industry.

5.1.3 Visualization technology-aided safety monitoring and warnings on site

Visualization technology has been proposed to aid on-site safety monitoring and early-warnings based on the integration of real-time worker locations [19,27,83] and motion [67,70,75], construction progress [73,74] and construction equipment operations [75,78,79] by combining other information or image technologies (see Table 1). However, existing research places more emphasis on worker location and less on their motion and postures (which have a serious impact on construction safety), more on crane operations and less on other equipment. Relevant sensor- or image-based data collection technologies are also insufficiently developed to support site monitoring, which has restricted the extensive application of visualization technology in practice.

5.2 Future research directions

5.2.1 A non-customized visual safety training approach

A generalized visual-interactive-cooperative safety training approach that is not customized for a specific scenario but suitable for the customization of different scenarios, needs to be explored and developed in the future for use by crane operators as well as iron workers for example. All the trainers would then need to do is to establish a specific scenario-based safety-training platform based on their own requirements. The trainees could experience a virtual-real environment and easily interact with the platform, with different trainees collaborating in completing specific scenario-based work using the platform. The aim is to improve safety training and reduce the costs involved. Such an approach could also be available for the acquisition of general safety knowledge as well as safety issues identified in a specific project.

5.2.2 An integrated-automated visual approach for JHA identification and management

JHA identification and management should cover most of the hazard areas during construction. In order to improve efficiency, a comprehensive safety rule database needs to be first established [84] that involves different construction components (beyond edges, holes, scaffolding and specific workspaces), various major accidents (beyond falling from height and those caused by structural collapse and spatial collisions) and relevant prevention measures (beyond protection guards such as fences for edges, holes and scaffolding). From this, a rule-based automated approach for JHA identification and protection layout could be developed that facilitates JHA identification and management for different construction projects and components [84].

5.2.3 Image-based automatic identification of worker unsafe motion

Considering its serious influence on construction safety, more emphasis needs to be placed on worker motion [19]. An efficient way would be to adopt image-processing technology to real-time monitoring of worker motion suitably parameterized for automatic identification. Image processing technology is traditionally time-consuming because of the excessive redundant information that occurs in pictures. Zainordin et al.'s [85] proposed image-parameterization approach - to determine human body posture by 22 parameters extracted in real time by a depth picture camera - should improve the efficiency of worker motion identification. Moreover, no wearable devices are needed that may interfere with normal site work.

5.2.4 An efficient approach for modeling real-time construction progress

It is important and necessary to monitor and model construction progress in real-time, since this provide the basic data needed for a continuous safety warning capability on site [21]. Considering the shortcomings of laser scanning technology (e.g. seriously affected by the line of sight and difficulty in identifying the properties of facility components), a comprehensive and efficient approach to real-time tracking and modeling construction progress needs to be studied in the future, which should be suitable for both prefabricated and cast-in-situ construction.

5.2.5 Monitoring the operations of construction equipment

The operations of equipment other than construction cranes (e.g. excavators) have seldom been considered in existing research, but nevertheless commonly lead to construction accidents.

Due to the uniqueness of different forms of equipment, it is necessary to develop a set of approaches to monitoring their operation. At the same time, current technologies still have low accuracy (sensor-based) or efficiency (image-based). Considering that sensor technology is not affected by line of sight and is highly efficient, multi-sensor-based monitoring approaches are clearly worthy of future study.

5.2.6 Extraction of safety knowledge from on-site visual safety-related data

The data obtained from the use of visualization technology in the automatic identification and storage of unsafe behavior or JHAs on site can be used to mine safety-related knowledge for future safety management [65]. For example, analysis of worker violation data can indicate the most dangerous time, the most dangerous area and the most dangerous worker – all of which are of great significance for safety management.

Table 1. Brief summary of existing research into visualization technology-based construction safety management

<table>
<tr><th colspan="2">Construction safety management</th><th rowspan="2">Achievement</th><th rowspan="2">Shortcoming</th><th rowspan="2">Literature</th></tr>
<tr><th>Period</th><th>Content</th></tr>
<tr><td rowspan="7">Pre-construction</td><td rowspan="3">Safety training</td><td>Visual safety training</td><td rowspan="3">Not comprehensive enough (particularly with interaction and cooperation), only involving:
(1) parts of equipment operations; and
(2) installation of precast elements.</td><td>[16,17,27,30,31,73,86]</td></tr>
<tr><td>Interactive safety training</td><td>[13,16,17,30-32]</td></tr>
<tr><td>Cooperative safety training</td><td>[17,33]</td></tr>
<tr><td rowspan="3">JHA identification</td><td>Automatic identification of falls from height</td><td rowspan="5">Not comprehensive and efficient enough:
(1) JHA identification only involves some types of accidents, e.g. falls from height, structural collapse and collisions between equipment;
(2) Automatic identification only involving falls from height and spatial collisions; and
(3) Automatic layout of protection guards only for edges, holes, scaffolding, etc.</td><td>[33,41,42,87-89] [90]</td></tr>
<tr><td>Identification of potential structural collapse</td><td>[47,48]</td></tr>
<tr><td>Automatic identification of spatial collision</td><td>[33,44]</td></tr>
<tr><td rowspan="2">JHA management</td><td>Visualization of identified JHAs</td><td>[50]</td></tr>
<tr><td>Automatic layout of protection guards and measures</td><td>[35,51,52,91]</td></tr>
<tr><td rowspan="2">In-construction</td><td rowspan="2">Monitoring worker behavior</td><td>Sensor-based monitoring of worker locations and motion</td><td rowspan="2">(1) More for location, and less for motion, only involving some postures; and
(2) Insufficient technologies, e.g. sensor-based technologies affecting normal work as well as low accuracy, image-based technologies being too slow and easily affected by line of sight.</td><td>[27,59,61-63,83]</td></tr>
<tr><td>Image-based monitoring of worker locations and motion</td><td>[70,71]</td></tr>
</table>

	Monitoring the construction environment	Monitoring a (relatively) static environment with laser scanner	(1) Modeling and schedule control: more rough and less detailed; and (2) Low efficiency of laser scanning, particularly not in real time.	[18,73-75]
		Monitoring the position and posture of equipment with sensors or laser scanners	(1) More for cranes and less for other equipment; and (2) Insufficient technologies, e.g. sensor technologies with low accuracy, slow image technologies and easily affected by line of sight.	[65,75,77-79]
	Safety warnings	Warnings of site JHAs	(1) Warnings of JHAs: mainly for structural stability (2) Warnings of unsafe behavior: more for worker location, and less for worker motion.	[37,80]
		Warnings of worker unsafe behavior		[19,21,65,83,92]

6. Conclusion

This paper reviews the application of visualization technologies to construction safety management from 2000 to 2015, involving 78 relevant papers contained in the *Web of Science* and *ASCE Library* databases. It is found that current research has employed visualization technology to assist in construction safety management during the pre-construction and in-construction periods, particularly focusing on both workers and environments, and improving the performance of safety management. During the pre-construction period, visualization technology can improve the performance of safety training in a visual, interactive and cooperative way, as well as facilitating JHA identification and management, improving the efficiency and effectiveness of accident prevention. During construction, visualization technology can aid in monitoring worker unsafe behavior and equipment operations and implement safety warnings in real time by a combination of sensors, laser scanners or image-based technologies.

The shortcomings of previous research are identified, for example, the lack of a comprehensive safety training approach, the limited types of accidents considered in JHA identification and management, incomplete on-site safety monitoring and warnings, and the limitations of present technologies. Future research directions are suggested, involving comprehensive safety training, automated JHA identification, the image-based automatic identification of worker unsafe motion, real-time modeling of construction progress, monitoring of various equipment and extraction of safety knowledge.

The main contribution of this paper is to reveal the state of the art of visualization technology-aided safety management in both theory and practice, as well in identifying possible future research directions, thus benefiting the extensive application of visualization technology in construction safety management. In addition, all leading published research relating to visualization technology in construction safety management is reviewed. Research not reviewed includes papers written in neither English nor Chinese and relevant patents.

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