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# 1 Visualization technology-based construction safety management: A review

2  
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7  
8 **Abstract:** Construction safety management has been a popular issue in research and practice in  
9 recent years due to the high accident and death rates in the construction industry. The complexity  
10 and variability of construction sites makes safety management more difficult to implement than in  
11 other industries. As a promising technology, visualization has been extensively explored to aid  
12 construction safety management. However, a comprehensive critical review of the visualization  
13 technology in construction safety management is absent in the literature.

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

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

## 25 26 1. Introduction

27 Construction has become one of the most dangerous industries due to the harsh work  
28 environment and high risks involved [1]. In China alone, there was an average of more than 2500  
29 annual accident deaths accompanied by serious safety accidents in the construction industry from  
30 1997 to 2014 (see Fig. 1)[2]. In addition to developing countries, the construction industry is also  
31 recognized as dangerous in developed countries such as U.S. and U.K. [3]. According to global  
32 statistical data, its accident death and injury rate is three and two times higher respectively than  
33 the average of other industries [4]. In spite of more attention being paid to safety management in  
34 recent years, the accident rate of the construction industry continues to be high [5].

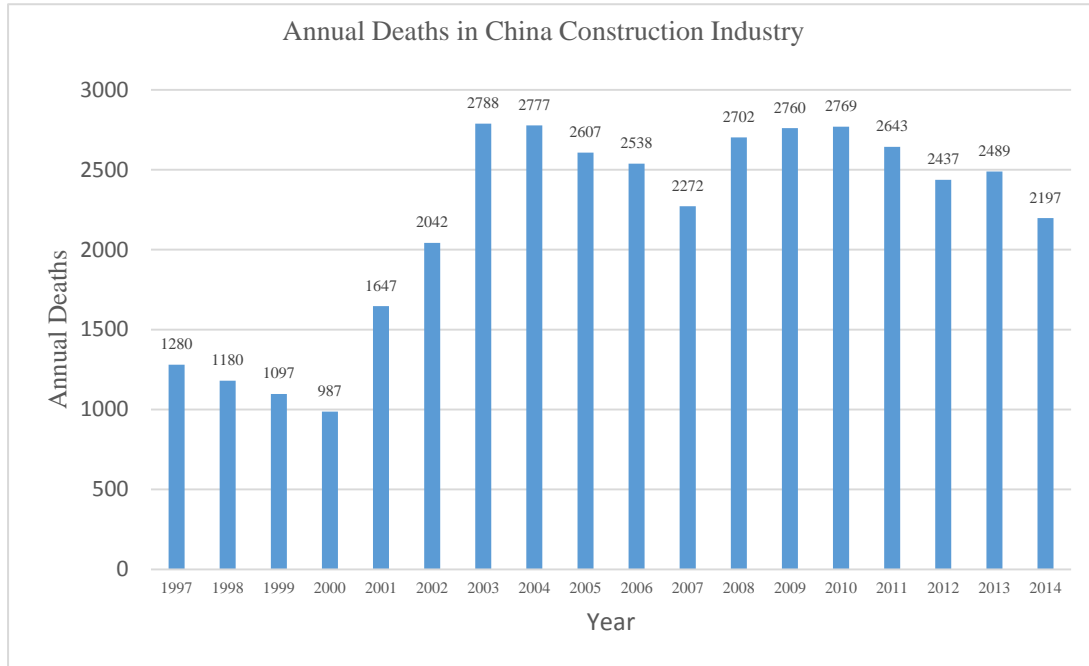


Fig. 1. Annual deaths in the China construction industry from 1997 to 2014

36

37

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

- 44 • *Insufficient safety training.* Safety training is regarded as a useful safety management method  
 45 [8], but is traditionally based on indoor teaching, which lacks interaction, intuition and  
 46 hands-on training, and therefore does little improve the safety consciousness of workers [9].
- 47 • *Incomplete safety planning.* Failing to identify safety hazards is a major cause of construction  
 48 accidents [10] and the identification of a job hazard area (JHA) can significantly improve  
 49 safety and decrease associated costs [11,12]. Traditionally, safety planning is based on a team  
 50 meeting [13] in which JHAs are identified by imagining construction processes with the aid  
 51 of 2D drawings, schedules, safety rules and experience, but lacking an intuitive method of  
 52 representing the construction process. A large number of JHAs also go undetected because of  
 53 the uniqueness, dynamism and complexity of the construction environment.
- 54 • *Invalid site monitoring.* Site monitoring is currently the key to safety management [9]. Safety  
 55 officers often use a checklist to manage construction safety by identifying and recording  
 56 violations [14]. In the absence of technological support, however, it is impractical to monitor  
 57 the whole of sites at once in this way due to their large size and dynamic environment [15].

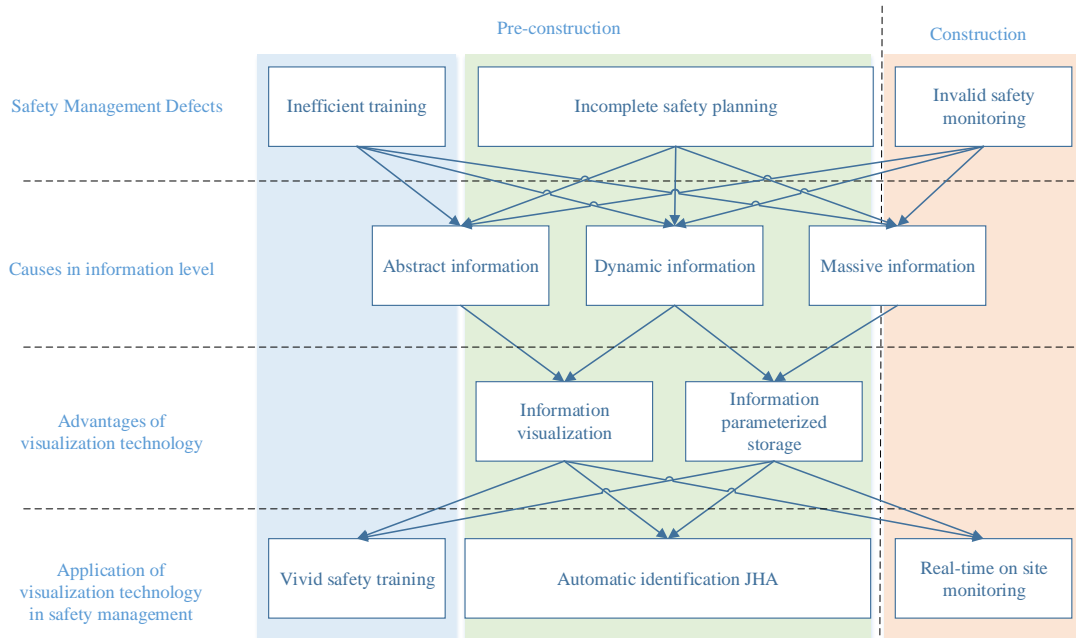
58 The above problems derive from the information level. Fig. 2 shows the features of  
 59 construction information, which is abstract, dynamic and massive. These features of construction  
 60 information impede construction training, planning and monitoring, since workers and safety  
 61 officers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

63 Current research is making some efforts to solve these problems with the help of

64 visualization technology, which not only makes information digital and visual, but also depicts the  
 65 construction environment and processes comprehensively and accurately. The main contributions  
 66 of visualization technology to safety management can be summarized as (Fig. 2):

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

77



78

79

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

80

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

89

## 90 2. Research method

91 According to Heinrich's safety theory, the cause of accidents involves unsafe objects and  
 92 worker behaviors [20], while safety management involves worker safety training, the

93 identification and management of JHAs during pre-construction and the monitoring of workers  
94 and construction equipment during the construction process [19,21]. In identifying the key  
95 research relating to the use of visualization technology, this paper provides a review in terms of  
96 these four aspects.  
97

## 98 2.1 Literature search

99 As Zhou et al. [22] allude, visualization technology involves BIM (Building Information  
100 Modeling), 4D CAD (Four-Dimensional Computer Aided Design), VP (Virtual Prototyping), VC  
101 (Virtual Construction), VR (Virtual Reality) and AR (Augmented Reality). BIM may be regarded  
102 as a visual database, integrating a building's dimensional and attribute information [23] and is  
103 often used in the static analysis and comparison of construction processes. 4D CAD, is widely  
104 used in construction[16] and provides schedule simulation by adding the schedule to 3D models,  
105 VC involves multi-dimensional construction process simulation that takes into account not only  
106 3D (or visual) and schedule information, but construction resources such as workers and  
107 equipment. Similar to VC, VP is often used to aid worker safety training [24] by focusing on  
108 dynamic changes in schedule, cost, resources, etc. - placing more emphasis on environment  
109 simulation to provide people with a feeling of telepresence [25]. Relevant publications were  
110 identified by searching the *Web of Science* and *ASCE Library* databases with the following  
111 keywords:

- 112 (1) Visualization technology: "BIM", "4D CAD", "VP", "VC", "VR", "AR" and  
113 "information technology", connected by "or"
- 114 (2) Research topic: "construction" and "safe\*" (meaning "safe" and its derivatives)
- 115 (3) Research field: "science technology" selected in the *Web of Science*
- 116 (4) Research direction: "engineering or computer science", "construction building  
117 technology", "automation control system", "telecommunication", "urban studies" and  
118 "science technology other topics" selected in the *Web of Science*.  
119

## 120 2.2 Overview of the literature

121 The search words helped to identify 78 relevant papers. These are summarized in Fig. 3 in  
122 terms of the number of annually publications from 1999 to 2015. The number of different  
123 visualization technologies used in these papers (Fig. 4) clearly indicates BIM, 4D and VR to be  
124 the most popular.  
125

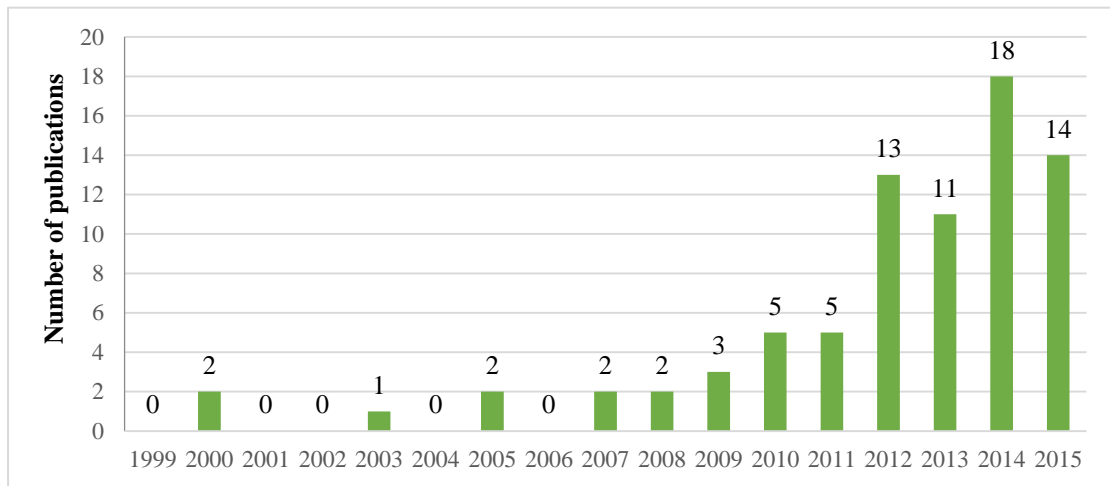


Fig. 3. Number of publications by year

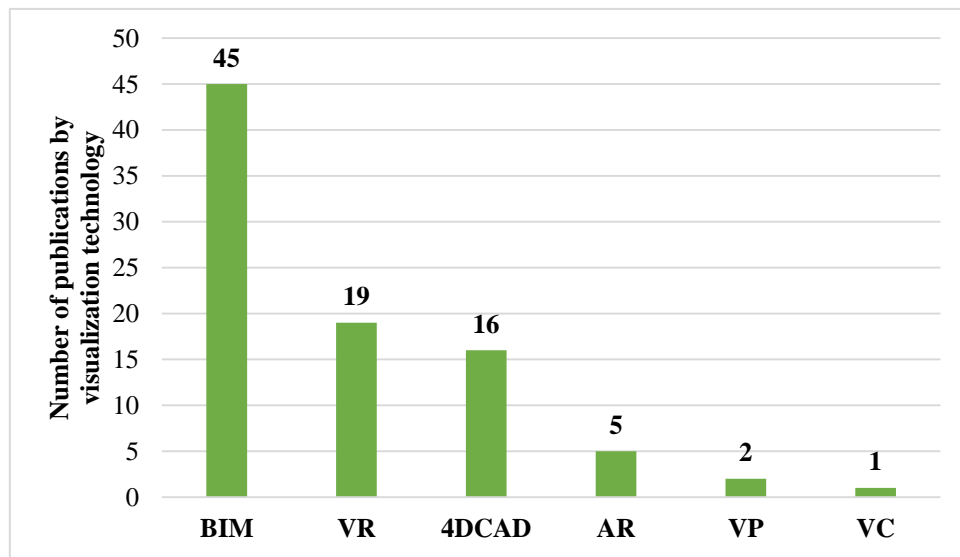


Fig. 4. Number of publications by visualization technology

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

140

141

142

### 143 3. Visualization technology and safety management during pre-construction

#### 144 3.1 Safety training

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

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

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

168 Visualization technology provides a cooperative approach for safety training. Many

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

176 In summary therefore, visualization technology combines safety-related project information,  
177 presents it in a visual model featuring interaction and cooperation and helps workers have a better  
178 understanding of safety knowledge or operations. As this is all realized by computers, the  
179 processes and results of the training can be recorded as the basis for safety management on site.  
180

### 181 3.2 *JHA identification and management*

182 A JHA refers to an area where potential job hazards lie and are usually a source of collision,  
183 edges and holes, as well as temporary structures. JHA identification and management is the  
184 foundation of safety training and construction site safety management, and in recent years  
185 visualization technology is starting to be employed to aid this process.  
186

#### 187 3.2.1 JHA identification

188 Visual technology offers a 3D and automatic approach to identifying JHAs on behalf of  
189 traditional 2D drawings or documents. For example, 3D building models can be used to assist  
190 safety officers in identifying JHAs in safety meetings [13,34]. Although this method improves the  
191 performance of JHA identification, it is also an experience-dependent manual process. In order to  
192 improve this, safety rules have been developed and integrated with visualization technology  
193 [35,36]. JHAs such as holes and edges can be automatically identified by referring to the building  
194 element information from 3D models and relevant safety rules [37,38]. As only building  
195 information is included in the method, it has been suggested that additional information  
196 concerning the site, temporary facilities, equipment, etc., should be integrated to provide the  
197 comprehensive identification of JHAs [39,40].

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

210 Building structures and temporary structures are also potential JHAs, as they need to be  
211 stable enough to avoid collapse during and after construction. 4D CAD, BIM and structural



212 analysis software have been integrated to simulate and analyze such possible collapses [46-48].  
213 Also, by integrating BIM with oxygen and temperature sensors, dangerous environment  
214 information can be identified and highlighted in the virtual model [49].

215

### 216 3.2.2 JHA management

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

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

236

## 237 4. Visualization technology and safety management in construction

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

246

### 247 4.1 On-site worker behavior monitoring

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

254 on-site safety management.

255

#### 256 4.1.1 Monitoring worker location

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

262

##### 263 (1) Sensor-based location

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

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

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

284

##### 285 (2) Image-based location

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

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

297

298 4.1.2 Monitoring worker motion

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

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

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

320

321 4.2 Environment monitoring on site

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

326

327 4.2.1 Monitoring static environments

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

332 *Manual simulation* uses electronic methods, such as scanning QR code (Quick Response  
333 code) [72], to record safety inspection information instead of by paper documents, but is still  
334 carried out manually by safety officers. *Semi-automatic methods* update the site 4D model daily  
335 [16], which is also a relatively slow process. *Automatic methods* obtain real-time information by  
336 images or other means and are much quicker. An Unmanned Aerial Vehicle (UAV) or Laser Scan  
337 shoot sites and capture site information by identifying feature points or lines in photographs  
338 [18,73,74]. However, this method involves a time lag due to the large number of points to be  
339 transmitted and analyzed. To solve this problem, a smart scanning method has been proposed that  
340 scans dynamic objects in real time and thus considerably decreases the number of points needed

341 [75]. Although these automatic simulation methods are quite efficient and accurate, the output  
342 model is only a shell – containing none of the parameters or attribute information necessary for the  
343 automatic identification of unsafe factors. Moreover, image-based technologies can operate only  
344 within line of sight, so it is difficult to build a parameterized model of the whole site with only one  
345 device. Thus on-site static environment information retrieval is still limited.

#### 347 4.2.2 Monitoring dynamic environments (equipment)

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

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

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

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

#### 367 4.3 Early warnings on site

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

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

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

386

## 387 **5. Discussion and future research directions**

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

392

### 393 *5.1 Discussion*

#### 394 5.1.1 Visualization technology-aided safety training

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

404

#### 405 5.1.2 Visualization technology-aided JHA identification and management

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

413

#### 414 5.1.3 Visualization technology-aided safety monitoring and warnings on site

415 Visualization technology has been proposed to aid on-site safety monitoring and  
416 early-warnings based on the integration of real-time worker locations [19,27,83] and motion  
417 [67,70,75], construction progress [73,74] and construction equipment operations [75,78,79] by  
418 combining other information or image technologies (see Table 1). However, existing research  
419 places more emphasis on worker location and less on their motion and postures (which have a  
420 serious impact on construction safety), more on crane operations and less on other equipment.  
421 Relevant sensor- or image-based data collection technologies are also insufficiently developed to  
422 support site monitoring, which has restricted the extensive application of visualization technology  
423 in practice.

424

425 5.2 *Future research directions*

426 5.2.1 A non-customized visual safety training approach

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

436

437 5.2.2 An integrated-automated visual approach for JHA identification and management

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

446

447 5.2.3 Image-based automatic identification of worker unsafe motion

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

456

457 5.2.4 An efficient approach for modeling real-time construction progress

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

464

465 5.2.5 Monitoring the operations of construction equipment

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

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

473

#### 474 5.2.6 Extraction of safety knowledge from on-site visual safety-related data

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

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

Construction safety management		Achievement	Shortcoming	Literature
Period	Content			
Pre-construction	Safety training	Visual safety training	Not comprehensive enough (particularly with interaction and cooperation), only involving: (1) parts of equipment operations; and (2) installation of precast elements.	[16,17,27,30,31,73,86]
		Interactive safety training		[13,16,17,30-32]
		Cooperative safety training		[17,33]
	JHA identification	Automatic identification of falls from height	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.	[33,41,42,87-89] [90]
		Identification of potential structural collapse		[47,48]
		Automatic identification of spatial collision		[33,44]
	JHA management	Visualization of identified JHAs		[50]
Automatic layout of protection guards and measures		[35,51,52,91]		
In-construction	Monitoring worker behavior	Sensor-based monitoring of worker locations and motion	(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.	[27,59,61-63,83]
		Image-based monitoring of worker locations and motion		[70,71]



	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	[37,80]
		Warnings of worker unsafe behavior	(2) Warnings of unsafe behavior: more for worker location, and less for worker motion.	[19,21,65,83,92]

## 485 **6. Conclusion**

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

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

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

510

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514

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