State-of-the-art analysis of the integration of Augmented Reality with Construction technologies to improve construction safety

Abstract:

Purpose – This paper aims to explore Augmented Reality (AR) applications in construction safety academic literature and propose possible improvements for future scholarly works. The paper explicitly focuses on AR integration with Construction 4.0 technologies as an effective solution to safety concerns in the construction industry.

Design/methodology/approach – This study applied a systematic review approach. Three hundred and eighty-seven potentially relevant articles from databases were identified. Once filtering criteria were applied, 29 eligible papers where selected. The inclusion criteria were being directly associated with construction safety, focused on an AR application, and AR interactions associated with the Construction 4.0 technologies.

Findings – This study investigated the structure of AR applications in construction safety. To this end, we studied the safety purposes of AR applications in construction safety: pre-event (intelligent operation, training, safety inspection, hazard alerting), during-event (pinpointing hazard), and post-event (safety estimation) applications. Then, the integration of AR with Construction 4.0 technologies was elaborated. The systematic review also revealed that the AR integration has contributed to developing several technical aspects of AR technology: display, tracking, and human-computer interaction. The study results indicate that AR integration with construction is effective in mitigating safety concerns; however, further research studies are required to support this statement.

Originality/value – This study contributes to exploring applications and integrations of AR into construction safety in order to facilitate the leverage of this technology. This review can help encourage practitioners and researchers to conduct further academic investigations into AR application in construction safety.

Keywords – Augmented reality, Mixed reality, Construction 4.0 technology, Safety

1. Introduction

The construction industry is a risky business worldwide (Sherratt *et al*., 2015). Accidents, injuries, and fatalities commonly occur, and accident rates are about twice those in non-construction sectors (Le *et al*., 2015). Also, it has been shown that safety on the construction site, on its own, has the non-negligible potential to improve workers' productivity (Hasanzadeh and De La Garza, 2020). Safety plans, such as inspection, training, and monitoring, have improved workers' awareness and behaviors toward the dangerous environment; however, the reported accident rates are still worryingly high (Guo *et al*., 2017b). Safety management related to a construction project is the most frequently used practice to control risks and reduce unsafe activities (Zhou *et al*., 2013). However, the high rates of construction site injuries and fatalities would indicate that commonly applied safety practices such as Personal Protective Equipment (PPE), education and safety regulations have not led to desired results (Harvey *et al*., 2001; Coglianese *et al*., 2003). To improve construction safety, information visualization practices have been incorporated into safety management techniques (Asadzadeh *et al*., 2020).

To date, to enhance working conditions for workers, advanced technologies, such as Augmented Reality (AR), have been considerably implemented. AR creates a context where digital data is superimposed on a mainly actual world view (Hou *et al*., 2014). Recently, AR technology has gained considerable attention from academics, who aim to provide an environment that enables worksite staff to communicate with each other regardless of distance (Lee *et al*., 2014). AR technology, which allows access to information and visual interaction, has the potential to provide efficacious ways to identify and mitigate hazards (Neville A. Stanton, 2013). AR has also been presented as an effective platform for training scenarios in construction (Wang and Dunston, 2007).

The construction industry is experiencing an ever-increasing growth in the integration of technologies throughout its fourth wave of technological advancement, known as Construction 4.0 technologies (El Jazzar *et al*., 2020). AR is seen as a core technology for this revolution (El Jazzar *et al*., 2020); the other Construction 4.0 technologies are: (1) Building Information modeling (BIM), by which a 3-dimensional (3D) model of the structure is created (Doan *et al*., 2020), (2) Virtual Reality (VR), which allows users experience a completely immersive virtual environment, (3) Robotics that duplicate human actions, (4) Artificial Intelligence (AI) that duplicates human cognitive ability, (5) Cloud to real-time information sharing, and (6) Internet of Things (IoT) which provides a persistent and intelligent connection between natural objects and a virtual model (Klinc and Turk, 2019; El Jazzar *et al*., 2020; Newman *et al*., 2020; ElMenshawy and Marzouk, 2021).

Several review studies have been carried out to identify existing AR applications for construction health and safety. For example, Li *et al*. (2018) and Moore and Gheisari (2019) presented an in-depth view of the theoretical synthesis of AR and VR applications by reviewing and classifying AR and VR applications in construction safety. Also, Guo *et al*. (2017a) and Gao *et al*. (2019) assessed the visualization in construction safety and found it an effective technology for training and reducing hazards on construction worksites. However, the integration of AR with the Construction 4.0 technologies has not been elaborated in previous review articles. As a result, the main aims of this study are to address the aforementioned limitation and gap by investigating the body of knowledge of AR applications in construction safety, and to guide future academic research directions. A systematic literature review may help academics and industry experts to uncover critical areas of study by providing them with a better perspective on the state-of-the-art of this field of study and the related challenges. Furthermore, investigating the connection between technologies contributes to collaborative research opportunities and is a primary way to meet the digital demands of Construction 4.0 advancement (El Jazzar *et al.*, 2020). This study, therefore, undertakes a review of previous studies on use of AR and to explore AR interactions with the Construction 4.0 technologies in construction safety literature.

It is essential to unambiguously clarify the differences between Mixed Reality (MR), AR, VR and Augmented Virtuality (AV) since they have become debated topics in the safety literature in recent years (Feng *et al.*, 2018; Li *et al.*, 2018; Bottani and Vignali, 2019; Lovreglio and Kinateder, 2020). All the systems present virtual objects to participants; however, they differ in how virtuality is linked to reality (Milgram and Kishino, 1994). VR presents artificial content without any interaction with the physical world, while MR contains aspects of the natural world, and incorporates facets of pure reality and pure virtuality (Carmigniani *et al.*, 2011). As shown in Figure 1, MR features reality and virtuality, and consists of AR and AV (Feng *et al.*, 2018). With AR, virtual contents are brought into an actual scene and most visual perception comes from the real world (Carmigniani *et al.*, 2011; Shanbari *et al.*, 2016; Flavián *et al.*, 2019). Conversely, AV, which is not discussed in this study, monitors some real elements in a predominantly virtual world (Ternier *et al.*, 2012).

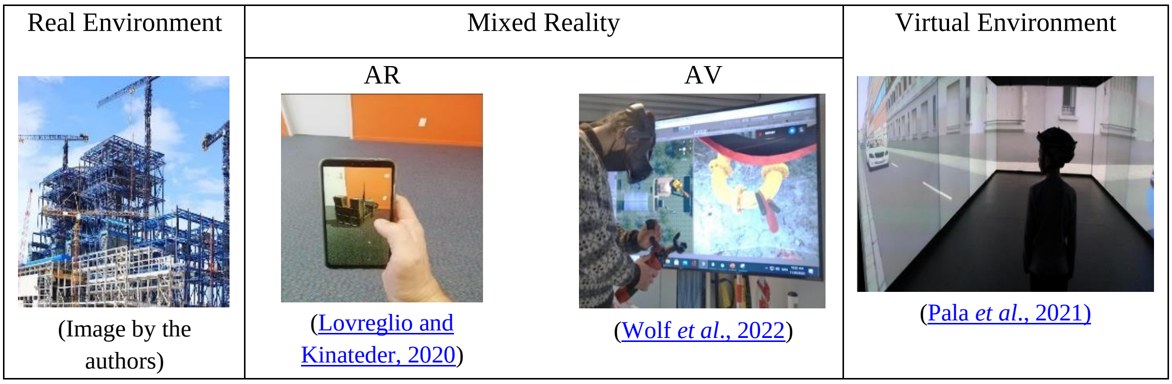

Figure 1 - Virtuality continuum by Milgram and Kishino (1994)

AR content can be displayed by video-see-through (VST), optical-see-through (OST) (Lovreglio and Kinateder, 2020), or projective AR devices (Zhang *et al.*, 2020). In a VST device, AR content is captured by a camera on a non-transparent screen, such as a smartphone or tablet (Lovreglio and Kinateder, 2020). In contrast, OST devices display AR objects onto transparent head-mounted devices, e.g., Magic Leap 1, Microsoft HoloLens 2, and Google Glass (Lovreglio and Kinateder, 2020); while projective AR utilizes projection equipment to demonstrate virtual objects in the natural environment (Zhang *et al.*, 2020). The correlation between the factual background and AR device outlook position is called "Registration" or "Alignment" (Mizuno *et al.*, 2004). The purpose of alignment is to orient superimposed virtual objects in accordance with reality (Behzadan and Kamat, 2007). Similarly, geometric registration between the live media content and rebuilt virtual model image is called "Tracking" (Bokhari *et al.*, 2020), and is aimed at finding a users' location to augment nearby related virtual models (Jian *et al.*, 2018). To this end, Kim *et al.* (2018) proposed three tracking technologies: vision-based, sensor-based, and hybrid tracking methods. In vision-based tracking methods, nearby visual characters (e.g., markers or unique objects) are used to identify the location. In sensor-based tracking methods, sensors like Global Positioning System (GPS), wireless sensors, Bluetooth, or radio frequency identification present specific location data (Kim *et al*., 2018). Hybrid tracking methods use both visual features and sensors (Kim *et al*., 2018).

2. Review Methodology

The methodology of this study follows the systematic principles presented by Kim *et al*. (2018). The method adopts a five-step process: (1) framing research questions and providing search keywords; (2) identifying databases and conducting an initial search; (3) evaluating the quality of the study; (4) summarizing the findings; and (5) interpreting the results.

This study explores AR interactions with Construction 4.0 technologies in construction safety literature. The paper analyses specific purposes to leverage AR technology, then reviews AR integrations with Construction 4.0 technologies in the previous studies of construction safety. Hence, the following research questions are applied:

Research Question 1 (RQ1): What are the specific aims of AR applications in construction safety academic literature?

Research Question 2 (RQ2): What Construction 4.0 technologies have been integrated with AR in construction safety academic literature?

To get the maximum coverage of publications and to address these research questions within academic literature, a comprehensive keyword search string was developed:

("*augmented reality*" OR *"mixed reality"*)

AND

("*construction*")

AND

("*safety*" OR "*health*" OR "*safe*").

The keywords were applied to databases in order to acquire relevant articles and exclude irrelevant results. A comprehensive exploration was conducted utilizing well-established databases—Google Scholar, IEEE Xplore, Web of Science, and Scopus. Also, citations of the most frequent review papers were manually added as a complementary method to cover any missing papers. This review focused on research articles published in peer-reviewed journals and conference proceedings.

Following the keyword search of the specified data sources and journals, 387 potentially relevant articles were extracted during the identification stage. The number of articles found in each database is shown in Figure 2. Specifically for Google Scholar, 15 pages with ten articles on each page were browsed, but the number of relevant articles significantly dropped after the first ten pages. As a result, the first 100 articles from this database were obtained initially. These 387 papers mentioned keywords in the title, abstract, or keywords. In this step, no other restrictions were imposed.

After removing duplicates, to evaluate the eligibility of the studies, the articles were manually checked by their abstracts, and those not directly associated with construction safety were filtered out. Afterward, the full text of the remaining articles was checked to determine if AR in construction safety and at least one of the research questions of this article were debated. Consequently, after the step-by-step evaluation of studies, 29 publications (hereafter called eligible papers) were identified. The procedure named Preferred Reporting Items for Systematic Literature Reviews and Meta-Analyses (PRISMA) (Moher *et al.*, 2010) was deployed to register this process (see Figure 2).

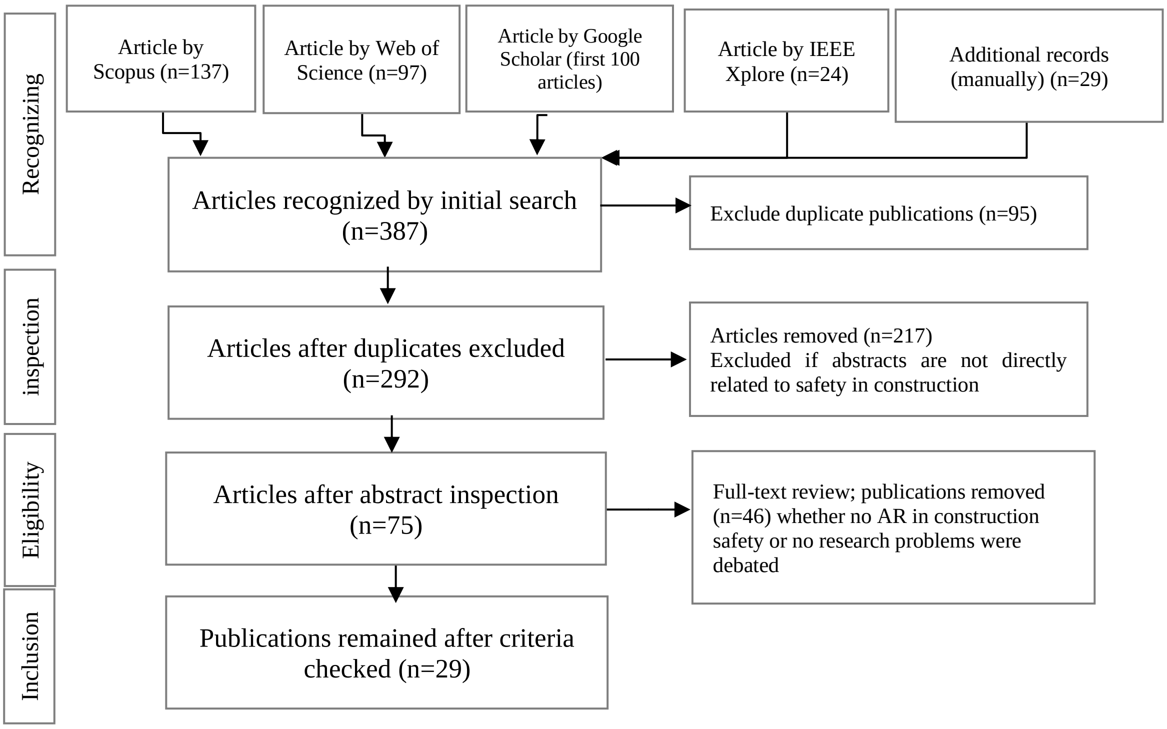

Figure 2 – A framework of systematic literature review

3. Results

In this step, the eligible papers were reviewed, and the evidence was consolidated from the academic literature to answer the two research questions pointed out in Section 2.

3.1 *Summarizing the Evidence*

The eligible papers were systematically classified to segregate the content and facilitate the interpretation of evidence. Table 1 provides a summary of the evidence retrieved from the eligible papers. Columns 1 and 2 demonstrate the complete safety applications of AR in construction (answer to research question 1). Safety aims of AR in construction safety are explicable in terms of pre-event, during-event, and post-event applications. Pre-event application refers to AR safety practices that prevent or minimize a construction-related-disaster in advance. Similarly, during-event and post-event applications are associated with safety AR applications when a disaster is happening and has occurred, respectively. Column 3 gives Construction 4.0 technologies integrated with AR in construction safety (answer to research question 2). The integrated technologies with AR consist of BIM, IoT, AI, Robotics and Cloud. These findings are introduced here and then interpreted in section 3.2.

Safety aims	Safety sub-aims	Integrated technologies with AR
Pre-event application	intelligent operation	BIM
	training	IoT
	safety inspection	AI
	hazard alerting	Robotics
During-event application	pinpointing hazard	Cloud
Post-event application	safety estimation	

Table 1: Summarizing evidence for each proposed research question

3.2 *Interpreting the Evidence*

This section discusses the outcomes of the eligible papers for each research question.

3.2.1 *Research question 1: What are the specific aims of AR applications in construction safety academic literature?*

As illustrated in column 1 in Table 1, specific aims of AR applications in construction safety are explicable in terms of pre-event, during-event, and post-event applications. The most common objective of eligible papers was pre-event applications with 26 out of 29 publications (89.7%), followed by during-event application articles with 2 out of 29 publications (6.9%). Finally, one article stressed post-event AR safety application (3.4%). Further details of all aims are discussed below.

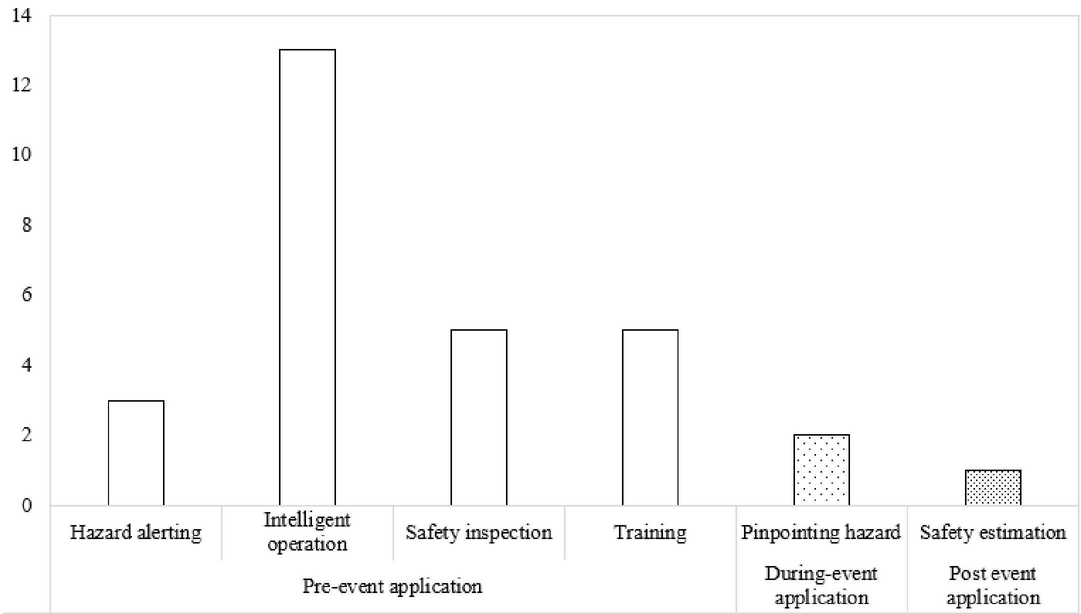

Figure 3: Number of publications per each safety sub-aims

3.2.1.1 Pre-event application

As shown in Table 1 and Figure 3, the purpose of pre-event applications fell into the following four groups, (1) intelligent operation, (2) training, (3) safety inspection, and (4) hazard alerting. To provide pre-event applications, as shown in Table 2, the publications most commonly focused on intelligent operation (13 out of 29, 44.8%), followed by training and safety inspection (each 5 out of 29, 17.2%), and finally, hazard alerting application (3 out of 29, 10.3%). Intelligent operation utilizing AR for construction workers, designers, engineers, and machinery operators is the most common safety application of AR in construction literature. AR has great potential to improve on-site performance and facilitate safety execution by augmenting virtual construction information onto the physical world in real-time (Park and Kim, 2013; Xiang *et al.*, 2021). For instance, to overcome low productivity in retrieving information and alleviating the mental workload of construction staff, Wang *et al.* (2014) presented an AR framework, which displayed as-planned data onto actual environments. Therefore, the participants could control inconsistencies between the actual and the scheduled progress (Wang *et al.*, 2014). Similarly, Foroughi Sabzevar *et al.* (2021) dealt with the traditional issue of construction staff-drawing sheets interaction. Specifically, interpreting two-dimensional (2D) drawings with different types of symbols and referencing may result in distraction and poor data transfer between the designers and construction crews (Foroughi Sabzevar *et al.*, 2021). To overcome this, Foroughi Sabzevar *et al.* (2021) developed and laboratory tested augmented virtual information that could be accessed on mobile phones.

To decrease construction information complexities for workers, by utilizing projective AR Xiang *et al.* (2019, 2021) developed and tested a visible to the naked eye prototype that superimposed virtual information onto the physical surface. The prototype provides designers and workers with a display of information in the exact location and enhances workers' productivity by identifying pipeline locations before or during installation on construction sites (Xiang *et al.*, 2019, 2021). In contrast to traditional AR applications, Ogunseiju *et al.* (2021) adopted digital twins to improve construction ergonomic risks associated with workers' postures. This prototype contributed to self-control ergonomic risk alleviation by visualizing worker body position as a virtual replica via the head-mounted device and wearable sensors (Ogunseiju *et al.*, 2021). To be more specific, posture evaluation techniques used in this study consisted of monitoring angles and holding times of body segments. The results of this study show that this prototype provides an opportunity to take self-corrective ergonomic actions (Ogunseiju *et al.*, 2021).

Through intelligent operation, three studies focused on facilitating machinery operator tasks by instant way-finding for crane operators (Lin *et al.*, 2020), remote control of cranes (Hasan *et al.*, 2021), and simulating equipment operation on construction sites (Kim *et al.*, 2012). In particular, to overcome the poor navigation skills of crane operators, Lin *et al.* (2020) proposed a vision-based AR prototype to present instant way-finding for crane operators during the construction phase. This method deployed BIM to avoid obstacles in the lifting environment and provide a safe route for crane operation (Lin *et al.*, 2020). Similarly, Hasan *et al.* (2021) proposed a prototype in which digital twin technology, AR, micro-controllers, and sensors were used to connect a virtual augmented crane with a real crane on the construction site. This connection provided designers and engineers with real-time knowledge and the possibility of remote controlling (Hasan *et al.*, 2021). In a similar way, Kim *et al.* (2012) tried to reduce the risk of equipment crashing into structural members by using visually collision analysis—specifically, by augmenting equipment in the construction environment and visually monitoring the likelihood of any collision.

Another four studies in the intelligent operation category facilitated accurate mapping of underground utilities onto AR devices for safe underground construction. Augmenting underground utilities contributed to preconstruction planning that minimized the risk of striking utilities during excavation or drilling (Su *et al*., 2013). As an example, Su *et al*. (2013) evaluated the technical feasibility of geospatial AR visualization in an ongoing excavation operation. In another example, AR was investigated to reduce the risk of utility strikes during directional drilling (Fenais *et al*., 2018; Fenais *et al*., 2020). Fenais *et al*. (2018) and Fenais *et al*. (2020) developed a prototype utilizing Geographic Information Systems (GIS) to collect data, external GPS devices to reduce positional error, Google Earth to store the data, and the AR system to map the data in real-time. These studies showed that AR is an acceptable and safe solution in underground activities (Fenais *et al*., 2018; Fenais *et al*., 2019; Fenais *et al*., 2020).

As shown in Table 2 and Figure 3, safety training via AR was the objective of 5 out of 26 publications within the pre-event application group. For example, to overcome the lack of skilled laborers, Kivrak and Arslan (2019) proposed an animation-based and in-place learning platform for facilitating construction site activities by using smart glasses through which workers could follow construction activities and learn while working. A similar study developed training complex procedures and operational tasks for workers by augmenting informative data associated with their duties into AR devices so as to avoid errors and failures during construction (Hou *et al*., 2017). Compared to traditional AR training applications, three studies introduced, tested, and evaluated panoramic AR to create a training-based experience of the construction site (Eiris *et al*., 2018; Pereira *et al*., 2018; Pereira *et al*., 2019). To be more specific, panoramic AR focused on training the workers via augmenting 360-degree safety information onto trainees' head-mounted devices to educate about the four leading hazards: falls, being hit, being caught, and electrocution (Eiris *et al*., 2018; Pereira *et al*., 2018; Pereira *et al*., 2019).

As demonstrated in Table 2 and Figure 3, safety inspection using AR was the main aim of 5 out of 26 publications within the pre-event application category. Safety inspection is necessary to alleviate or eliminate dangerous construction situations (Zhou *et al*., 2017; Bokhari *et al*., 2020). AR has begun to assert itself in facilitating safety inspection; for example, Bokhari *et al*. (2020) and Khairadeen Ali *et al*. (2021) used vision-based AR systems by which safety inspection was performed using 3D scanning and photogrammetry technologies to address risks of traditional in-person inspection such as physical interaction between construction crew and inspector and loss of safety and productivity due to physical observation. In these two studies, 3D computer models were generated from captured photos using point cloud technology; subsequently, possible differences between as-planned and as-built could be augmented via VST AR devices and be transferred from the job site to the construction office and vice versa (Bokhari *et al*., 2020; Khairadeen Ali *et al*., 2021). Similarly, Zhou *et al*. (2017) investigated the feasibility of safety inspection of construction elements in underground tunneling via vision-based AR. From the field experiment results of these studies, safety discrepancy monitoring of built and planned construction modules was enhanced (Zhou *et al*., 2017; Bokhari *et al*., 2020; Khairadeen Ali *et al*., 2021). Two other studies employed AR to alleviate the risk of inspection in inherently hazardous areas and reduce the cognitive workload of inspectors by assisting safety rebar inspection prior to concrete casting (Hsu and Hsieh, 2019; Abbas *et al*., 2020). The methodology of these studies focused on monitoring superimposed planned rebar drawings onto built physical objects.

Hazard alerting communication by AR was the objective of 3 out of 26 publications within the pre-event application category (see Table 2 and Figure 3). Informing workers automatically about possible dangers on construction sites is essential in the health and safety domain (Kim *et al.*, 2017). To do so, Kim *et al.* (2017) and Baek and Choi (2020) proposed an AR system that provides workers with a wearable device that, via augmenting hazard data, helps with proactive hazard identification aimed at avoiding dangers arising from vehicles and heavy equipment. In the laboratory experiment conducted by Kim *et al.* (2017), the vision-based AR module displayed adequate safety data such as danger location and distance by calculating the distance between workers and vehicles in aboveground projects. In another study, a smart glasses proximity-warning platform, which receives Bluetooth signals attached to moving objects, was developed and tested by Baek and Choi (2020) in underground projects. Similarly, Sabeti *et al.* (2021) improved the proximity-warning system and conducted a field experiment integrating AR and AI.

Safety aim	% of publications	Publications
intelligent operation	44.8%	(Kim *et al.*, 2012; Park and Kim, 2013; Su *et al.*, 2013; Wang *et al.*, 2014; Fenais *et al.*, 2018; Fenais *et al.*, 2019; Xiang *et al.*, 2019; Fenais *et al.*, 2020; Lin *et al.*, 2020; Foroughi Sabzevar *et al.*, 2021; Hasan *et al.*, 2021; Ogunseiju *et al.*, 2021; Xiang *et al.*, 2021)
training	17.2%	(Hou *et al.*, 2017; Eiris *et al.*, 2018; Pereira *et al.*, 2018; Kivrak and Arslan, 2019; Pereira *et al.*, 2019)
safety inspection	17.2%	(Zhou *et al.*, 2017; Hsu and Hsieh, 2019; Abbas *et al.*, 2020; Bokhari *et al.*, 2020; Khairadeen Ali *et al.*, 2021)
hazard alerting	10.3%	(Kim *et al.*, 2017; Baek and Choi, 2020; Sabeti *et al.*, 2021)
pinpointing hazard	6.9%	(Olorunfemi *et al.*, 2018; Dai *et al.*, 2021)
safety estimation	3.4%	(Kamat and El-Tawil, 2005)

Table 2: Safety aims of AR applications

3.2.1.2 During-event application

In contrast to numerous pre-event construction safety publications, during-event safety applications were the sole objective of only 2 out of 29 (6.9%) of eligible papers. Effective pinpointing hazards is critical to minimizing danger in construction sites (Dai *et al.*, 2021). Dai *et al.* (2021) conducted an AR communication-based experiment via an optical-see-through (OST) device to determine whether AR enhanced the suitability, accuracy, and ease-of-use of hazard pinpointing on construction sites. The trials and feedback from participants of this study showed that AR provided satisfactory safety and performance metrics compared to conventional methods such as phone calls, walking to people and talking, and video conferencing (Dai *et al.*, 2021). Another AR during-event application was developed and tested by Olorunfemi *et al.* (2018) to enable visual interaction and remote collaboration when pinpointing hazards. This article improved visually risk-based communication on construction sites via smart glasses. The outcome of this study demonstrated effective message delivery and message understanding by using AR in case of hazard.

3.2.1.3 Post-event application

Post-event construction safety application was the aim of one article among 29 eligible papers (3.4%). Kamat and El-Tawil (2005) applied AR to real-time damage assessment of under-construction structures after natural or artificial disasters. This prototype allowed construction managers to estimate the safety of the building via the OST AR device, and to make on-site decisions on whether to continue the construction operation or leave the hazardous environment if critical structural members failed (Kamat and El-Tawil, 2005). The AR technology used in this study was to superimpose previously-stored building information onto an actual building to evaluate structural integrity by comparing critical discrepancies between a baseline image and the objective view (Kamat and El-Tawil, 2005). The preliminary results of this study showed that the proposed AR-based post-event safety estimation was practical for real-time damage assessment (Kamat and El-Tawil, 2005).

3.2.2 *Research question 2: What Construction 4.0 technologies have been integrated with AR in construction safety academic literature?*

The eligible papers were analyzed to explore the implemented Construction 4.0 technologies alongside AR in safety construction. After reviewing eligible papers, as illustrated in column 3 in Table 1, five technologies emerged; (1) BIM, (2) IoT, (3) AI, (4) Robotics, and (5) cloud. As shown in Table 3 and Figure 4, 17 out of 29 publications (58.6%) articles focused on BIM technology integration followed by robotics, IoT, and AI, each with 2 out of 29 publications (6.9%), and finally, cloud sharing technology was the solution of one study (3.4%). Nine publications (31%) did not incorporate any Construction 4.0 technologies with AR. The classifications are not mutually exclusive—several publications integrated AR with multiple technologies. AR has shown great potential for blending with other technologies to improve safety performance on construction worksites. BIM was considered a core technology that collaborated with AR (Zhou *et al*., 2017). 3D models established on AR devices have been widely accepted in the construction industry (Zhou *et al*., 2017). For example, Kim *et al*. (2012) deployed BIM as a significant component to create 3D models of equipment that could be augmented via AR devices in order to monitor the possibility of collisions between structural members and virtual 3D models of equipment. In a similar article, since dealing with 2D drawings resulted in increasing the cognitive workload of the construction crew, Wang *et al*. (2014) applied BIM technology to create a detailed 3D model of a whole structure, which was registered via an AR device, that could be superimposed onto the physical construction worksite.

Technologies	% of publications	Publications
BIM	58.6%	(Kamat and El-Tawil, 2005; Kim *et al.*, 2012; Park and Kim, 2013; Wang *et al.*, 2014; Hou *et al.*, 2017; Zhou *et al.*, 2017; Fenais *et al.*, 2018; Hsu and Hsieh, 2019; Xiang *et al.*, 2019; Abbas *et al.*, 2020; Bokhari *et al.*, 2020; Fenais *et al.*, 2020; Lin *et al.*, 2020; Foroughi Sabzevar *et al.*, 2021; Hasan *et al.*, 2021; Khairadeen Ali *et al.*, 2021; Xiang *et al.*, 2021)
IoT	6.9%	(Hasan *et al.*, 2021; Ogunseiju *et al.*, 2021)
AI	6.9%	(Ogunseiju *et al.*, 2021; Sabeti *et al.*, 2021)
Robotics	6.9%	(Xiang *et al.*, 2019, 2021)
Cloud	3.4%	(Fenais *et al.*, 2019)

Table 3: Construction 4.0 technologies incorporated with AR

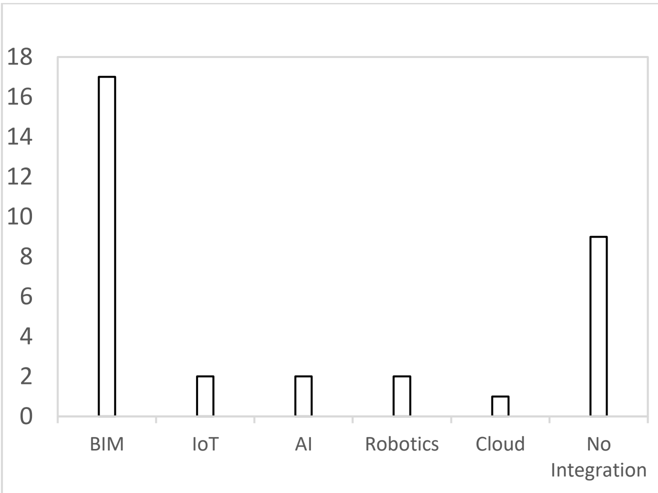

Figure 4: Number of publications for AR integration

In two other studies, IoT technology was adopted to develop a cyber model in which physical objects and virtual models were linked together (Hasan *et al.*, 2021; Ogunseiju *et al.*, 2021). To this end, IoT contributed to transferring real-time data between actual objects and cyber models (Hasan *et al.*, 2021; Ogunseiju *et al.*, 2021). For instance, Hasan *et al.* (2021) integrated IoT and AR to propose a cyber-physical platform where construction equipment could be monitored and controlled remotely. Similarly, Ogunseiju *et al.* (2021) developed a bi-directional communication system by combining IoT and AR and enabled workers to monitor their body postures and avoid ergonomic injuries.

Two other studies implemented AI alongside AR in order to create a system in which the cognitive function of humans could be duplicated and augmented onto wearable AR devices (Ogunseiju *et al.*, 2021; Sabeti *et al.*, 2021). Sabeti *et al.* (2021) presented a platform using AI technology for real-time moving vehicle detection to enhance workers' safety and minimize the possibility of fatal accidents in the construction environment by informing workers about hazards in their vicinity via their AR device. The preliminary results of this study show that the integration of AR and AI can provide construction staff with an opportunity to react to identified hazards (Sabeti *et al*., 2021).

Integration of robotics and AR was the other interaction studied by two publications. In contrast to AI, robotics duplicates the actions of a human, so Xiang *et al*. (2019, 2021) used robotics technology to design a prototype in order to overcome AR-related concerns such as weight and restricted field of view while wearing a head-mounted AR device. These studies demonstrated that AR, mounted on a robot, provided promising safety outcomes in construction worksites (Xiang *et al*., 2019, 2021).

Consolidation of cloud and AR was the primary integrating means of one article among eligible papers. To improve the accessibility of information, Fenais *et al*. (2019) designed a cloud-based technology through which real-time augmented virtual objects are stored and shared with construction managers.

4. Discussion

AR integration with Construction 4.0 technologies has evidence to support its potential for construction safety. Therefore, this section discusses AR incorporation with Construction 4.0 technologies from several vital aspects that enhance safety at construction sites. According to the literature, there are three technical aspects of AR applications; display, tracking, and human-computer interaction (Zhang *et al*., 2020). It is perceived that technology integration has the potential to enhance these three features and has led to improved safety on construction sites. Details of these aspects are discussed below.

4.1 *Display*

The prime technical aspect of the AR system is the display technology employed to visualize virtual objects in such a way that users consider these objects as part of the natural environment (Zhang *et al*., 2020). VST vs. OST usage among the eligible papers is about the same; 55% used VST devices, and 48% used OST as the display technology. The classifications are not mutually exclusive; several publications used VST and OST devices. Compared to the VST device, the OST device provides users with a greater sense of reality (Rolland and Fuchs, 2000); however, there are problems such as delayed display and inappropriate matching (Rolland and Fuchs, 2000). IoT technology has been integrated with AR to overcome delayed presentation and enhance the sense of reality (Hasan *et al*., 2021; Ogunseiju *et al*., 2021). IoT contributes to transferring real-time data between actual objects and cyber models (Hasan *et al*., 2021; Ogunseiju *et al*., 2021).

A study by Dai *et al*. (2021) demonstrated that limited the field of view was the most unfavorable response by participants when wearing AR glasses. Therefore, Xiang *et al*. (2019, 2021) stressed this issue and proposed a projective AR device that integrates AR and Robotics. These studies demonstrated that AR, mounted on a robot, provides promising safety outcomes on construction worksites.

Compared to OST and VST, projective AR has no profound connection between the device and the user. As a result, it can be extended to multiple participants and allows cooperation between users (Zhang *et al*., 2020). In addition, projective AR has the advantage of increasing safety performance and alleviating cognitive workload (Baumeister *et al*., 2017). Robotics can play a critical role in display technology and needs further investigation in the field of construction safety.

4.2 *Tracking*

The sensor-based method is a common tracking solution for outdoor AR applications (Su *et al.*, 2013; Fenais *et al.*, 2018; Bokhari *et al.*, 2020; Fenais *et al.*, 2020); however, there was a shift in the position of the data from three to four meters because of sensor accuracy issues (Quezada-Gaibor *et al.*, 2021). Tracking near tall buildings affects accuracy since these structures can block sensor signals (Fenais *et al.*, 2019; Quezada-Gaibor *et al.*, 2021). Similarly, the vision-based tracking method fails when the marker is blocked, or light is insufficient (Zhang *et al.*, 2020). As a result, Xiang *et al.* (2021) used a hybrid tracking method in which sensor data is used alongside a vision-based method; however, it took about five seconds to track the user's position (Xiang *et al.*, 2021). Ogunseiju *et al.* (2021) and Hasan *et al.* (2021) integrated AR with IoT to ensure continuous and accurate tracking between the AR device location and virtual object. The proposed sensing system showed promise for tracking corresponding virtual objects (Hasan *et al.*, 2021; Ogunseiju *et al.*, 2021).

4.3 *Human-computer interaction*

Human-computer interaction aims to provide operators with efficient and user-friendly performance (Ziegler, 1996). However, the study results conducted by Olorunfemi *et al.* (2018) showed that AR training for workers lacking adequate knowledge of the technology could affect users' performance and contribute to bias towards AR technology. As a result of this unwillingness, users' perceptions, responses, and judgments may differ from person to person (Olorunfemi *et al.*, 2018). To improve users' perception and enhance their awareness, Sabeti *et al.* (2021) integrated AR with AI and proposed a user-centered system in which the end-user received safety notifications directly from the AI component. The outcome of this study demonstrated that users felt an effective interaction with the incorporation of AI and AR (Sabeti *et al.*, 2021).

The survey questionnaire used by Dai *et al.* (2021) showed that the non-negligible weight of wearable AR devices prevented users from wearing and walking comfortably. As a result, AR integration with Robotics has the potential to assist humans in blending virtual objects into the real environment while avoiding a substantial physical workload (Xiang *et al.*, 2019, 2021).

Hasan *et al.* (2021) presented the integration of AR and IoT, which enabled construction crews to monitor and remotely operate heavy equipment. The main result of this study supports the proposition that IoT and AR integration provides promising outcomes in human-computer interaction (Hasan *et al.*, 2021). Similarly, Ogunseiju *et al.* (2021) showed that this integration could promote human-machine interaction by providing actionable data in a format understandable by humans. Moreover, Fenais *et al.* (2019) established an interactive cloud-based AR application that construction staff could instantaneously share, add to and edit data through the cloud system.

5. Conclusions

The construction industry involves many potential hazards, which are dangerous to workers, engineers, and supervisors. AR technology provides researchers and safety engineers with a powerful visualizing feature. This study reviews existing publications on AR applications in the construction safety field. Consequently, we introduced a comprehensive classification of AR applications in construction safety, and provided insights into the effectiveness and potential of AR integration with Construction 4.0 technologies.

As discussed in Section 3, the purposes of AR applications in construction safety were divided into pre-event, during-event, and post-event applications. Pre-event applications were further divided into intelligent operation, training, safety inspection, and hazard alerting. Furthermore, the objectives of during-event and post-event applications of AR were identified as pinpointing risk and safety estimation, respectively (see section 3.2.1). Likewise, five Construction 4.0 technologies have been integrated with AR—BIM, IoT, AI, robotics, and cloud (see section 3.2.2). However, the evidence to support the potential of AR integration is still somewhat limited. Based on the results from the systematic literature review, apart from BIM, which is seen as the core technology of AR, other Construction 4.0 technologies integrated with AR to cater to various pre-event safety demands focused only on intelligent operation and hazard alerting. Therefore, other identified application domains, training, safety inspection, pinpointing risks, and safety estimation, have not been investigated through AR integration with Construction 4.0 technologies. Specifically, the post-event application of AR is limited to one article. Thus, there is lack of evidence that would allow for conclusive assessment of the potential and effectiveness of AR integrations.

Further, AR incorporation in terms of vital technical aspects was discussed, and three technical aspects of the display, tracking, and human-computer interaction were elaborated. The key contribution of this research is that although few studies integrated AR, this incorporation showed promising safety results in construction sites and helped advance AR technology. Additionally, this paper opens up a window for future academic research, and shows that more study is necessary to produce sufficient evidence of the value and benefits of integrating AR with Construction 4.0 technology.

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