A Review of Using Augmented Reality to Improve Construction Productivity

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Abstract:
Low productivity has been a long-term issue in the construction sector. Human-made errors, lack of experience, and poor management are the common factors that cause low productivity. Low productivity can result in significant delays and economic losses to construction projects. Researchers have introduced innovative approaches to improve construction productivity, such as Augmented Reality (AR). Previous studies focused on state-of-art AR applications in different construction domains. There is little literature review studying AR applications in construction activities from the technical aspect and impact on productivity. This paper reviews AR technologies in the planning, design, and construction phases of construction projects and studies the leverage of AR technologies in improving construction productivity. This paper classifies AR applications by features that facilitated construction activities and improved productivity factors. This paper demonstrates the capability of AR to improve construction productivity.

Keywords:
Augmented reality, construction industry, literature review, productivity

1 Introduction

Poor productivity has always been a critical problem in the construction industry (Woetzel et al., 2017). Innovation is urgently needed to overcome this issue. Over the last decade, the rapid development of Information and Communication Technology (ICT) has accelerated the arrival of the Fourth Industrial Revolution (Industry 4.0) with cyber-physical systems being the essential features (Lasi et al., 2014). One of the emerging technologies to facilitate cyber-physical systems is Augmented Reality (AR). AR is a technology that superimposes virtual objects into the real world, which enables interaction with virtual objects and enhances users' perception of reality. AR applications have been widely used for the assembly and maintenance in the manufacturing industry (Egger and Masood, 2020). . Although the construction industry is behind other industry, such as healthcare and retail adopting AR solutions, more studies have focused on utilising technology in the construction industry (Noghabaei et al., 2020). AR could be a useful tool to facilitate information flow and exchange for construction activities. Nassereddine et al. (2020) reviewed 23 AR use cases in the construction industry and found that AR can enhance decision-making, improve collaboration and communication, improve productivity, and reduce rework. Rankohi and Waugh (2013) reviewed AR applications in architecture, engineering, construction and facility management disciplines. The result showed that previous studies were highly interested in monitoring project progress through superimposing the as-planned and as-built status. Wang, et al. (2013) reviewed hundreds of journal articles on AR applications in built environments published between 2005 and 2011.

They classified AR applications according to their concept, implementation, evaluation, and industrial adoption. The result showed that most studies were still in the evaluation layer and no study was in the industrial adoption layers. Li et al. (2018) studied several AR prototypes for construction safety management. They found that safety inspection and hazard identification were the major domains applied to AR. Hajirasouli, et al. (2022) reviewed AR applications in the design and construction phases and illustrated AR's benefits. They demonstrated that AR might reduce cognitive workload and data overload in heavy machine operation and assembly tasks. Moreover, Xu and Moreu (2021) reviewed AR applications in civil infrastructure construction and found that underground utilities, structure health detection and discrepancy check were the main research areas. The literature demonstrates that AR applications are becoming popular in the construction industry. AR has different forms, features, and capabilities to assist in construction activities. However, the technical details of AR for different types of construction activities remain unclear. More importantly, there is little evidence on whether AR applications can improve productivity in the construction industry. This study aims to bridge the gap by conducting a literature review. Three research questions were raised: (1) What construction activities have been investigated with AR applications? (2) How can AR applications be utilised in those construction activities? (3) How can AR applications impact the productivity of those construction activities? By answering the research questions, this study classifies AR applications based on their features and use cases (i.e., construction activities). This study reveals the impact of AR applications on the productivity of construction activities.

2 Methodologies

This study follows the literature review method proposed by Khan et al. (2003). Scopus and Web of Science were used as the databases. Both journal articles and conference papers were considered in this literature review. The first part of the search keywords is: "augmented reality" OR "mixed reality" OR AR. We included mixed reality because there is a mixed used of mixed reality and augmented reality in the literature since mixed reality shares a similar meaning to augmented reality. In many cases, mixed reality is the superset of virtual reality and augmented reality (Azuma, 1997). The second part of the search keywords is: "construction industry" OR AEC OR "civil engineering". In order to obtain the maximum coverage of the literature about AR and construction, we did not use any further keywords (e.g., productivity) to narrow down the search. An operator, AND, was used to combine search keywords. The search fields were set to titles, abstracts, and keywords. The search was conducted in November 2021. There were 345 results returned from Scopus and 624 from Web of Science.

The Preferred Reporting Items for Systematic Literature Reviews and Meta-Analyses (PRISMA) approach was used to filter the search results (Page et al., 2021), as shown in Figure 1. Firstly, 127 duplicates were removed. Secondly, articles were removed if they met the following exclusion criteria: (1) The article has no relation to augmented reality. (2) The article does not propose an AR-based prototype. (3) The proposed prototype is not designed to assist construction activities. For instance, articles focused on education or training were removed.

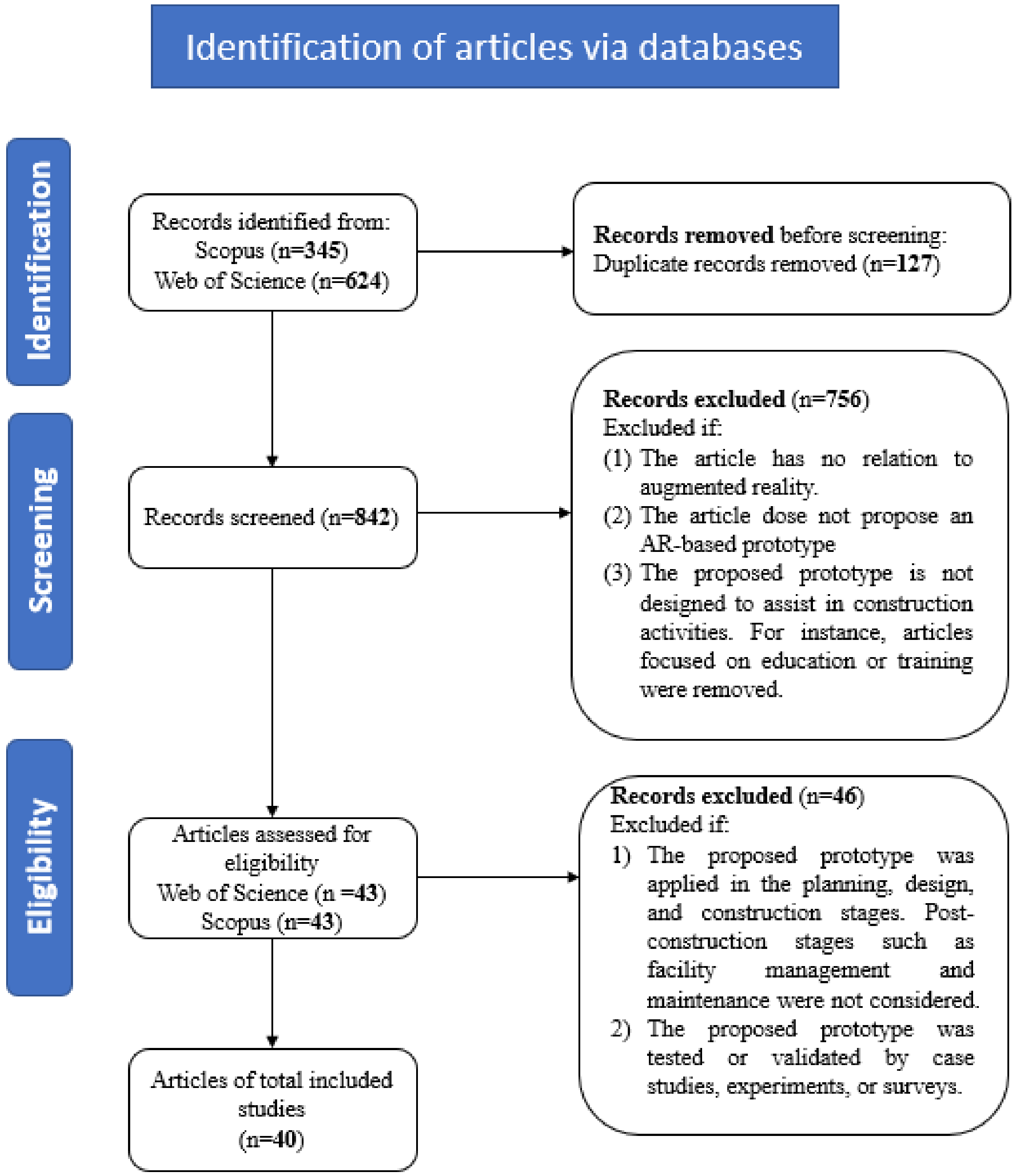

Figure 1. PRISMA methodology flowchart

In this step, 756 articles were excluded, with 43 remaining from Scoups and 43 from Web of Science. Lastly, we read the full text of the remaining 86 articles and applied the following inclusion criteria: (1) The proposed prototype was applied in the planning, design, and construction stages. Post-construction stages such as facility management and maintenance were not considered. (2) The proposed prototype was tested or validated by case studies, experiments, or surveys.

As a result, 40 articles remained, consisting of the eligible papers for this literature review. The eligible articles contain 30 journal articles and ten conference papers published between 2007 and 2022 (Figure 2).

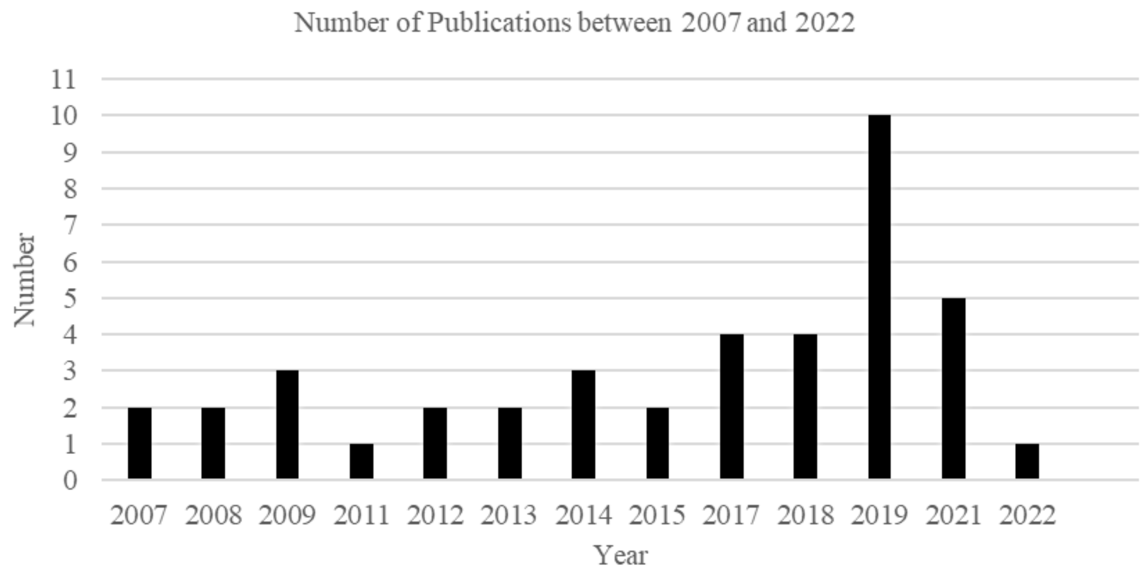

Figure 2. Number of publications from 2007 to 2022

3 Results

Based on the eligible articles, this study analyses the features, displays, processes, and tracking methods of AR prototypes (Figure 4). The width of the node represents the number of articles. Then, this study investigates the impacts of AR applications on the productivity of construction activities by studying the experiment in each article.

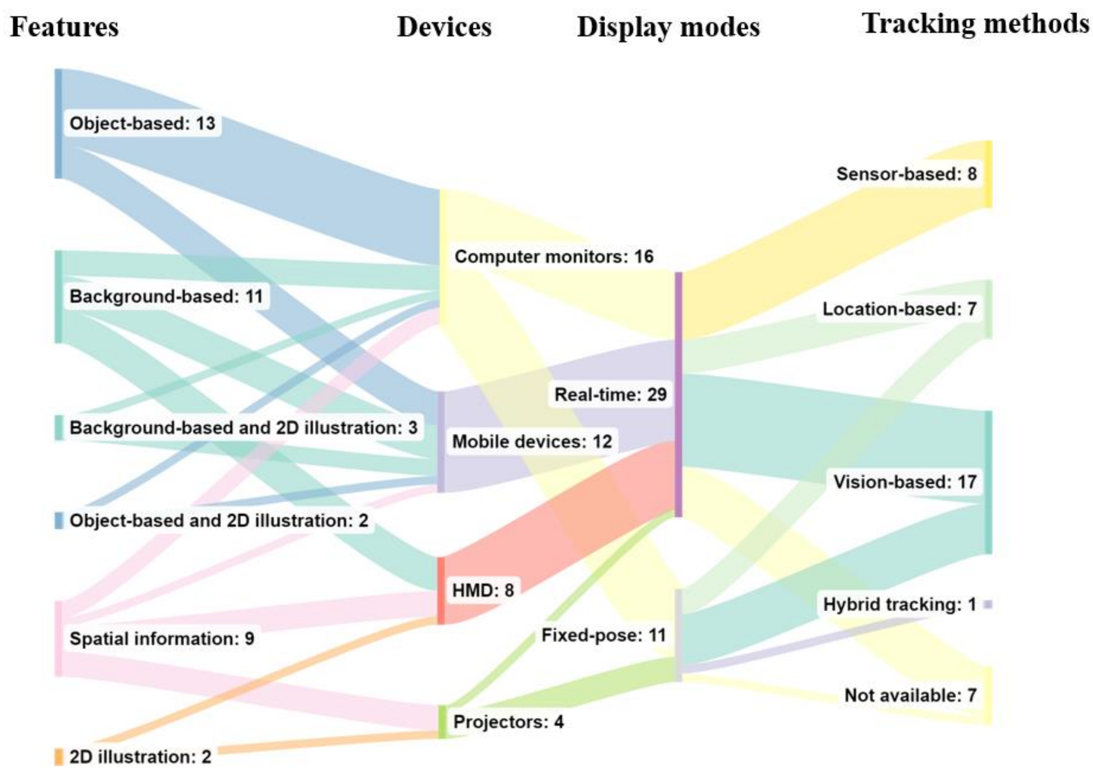

Figure 3. The connection between AR functions, display modes, and tracking methods

3.1 Features

This study identifies four major features of AR from the eligible articles: background-based, object-based, spatial information, and 2D illustration. The background-based feature means that real-world images or videos are used as the background of virtual content. The virtual content do not have real-time interaction with the real world. For instance, designers can stand around a table and visualise a 3D model on top of a 2D drawing via smartphones (Garbett et al., 2021). One advantage of using background-based AR is that users can perform physical measurements and interaction with virtual models in the real world. For instance, users can review the maintainability issues in their design by viewing a virtual model and checking if the facilities are reachable by their hand (Khalek et al., 2019). Users can use their arms to reach out and gauge the distance between themselves and virtual objects. Also, users can review virtual models while carrying out other works in the real world (Hui and Ieee, 2015, Sangiorgio et al., 2021). In some cases, a real-world image provides an intuitive feeling for users to interact with virtual models. According to this review, 14 of 40 articles propose AR prototypes based on this feature. The most popular construction activities facilitated by this feature include construction site transport simulation (Chen and Huang, 2013, Behzadan and Kamat, 2008), and heavy equipment operation simulation (Wang et al., 2022, Kim et al., 2012, Hammad et al., 2009).

The object-based feature means that virtual objects are overlaid or superimposed onto real-world objects. Benefiting from this, users can inspect the misalignment of constructed building components against design models by overlaying virtual models onto real-world objects (Mirshokraei et al., 2019, Georgel et al., 2007, Kumar et al., 2019, Shin and Dunston, 2009). Zhou et al. (2017) proposed an AR prototype based on this feature to check the displacement of adjacent tunnel segments. This prototype casts a geometric shape over tunnel segments, which requires a highly accurate tracking method. In addition to site inspection, this feature enables construction progress monitoring. Users can superimpose as-planned building models onto as-built buildings in the real world (Mani et al., 2009, Golparvar-Fard et al., 2011, Jiao et al., 2013). Moreover, this feature allows real-time interaction. For instance, AR-based interactive design permits users to annotate the virtual models superimposed onto the building components and support site documentation (Zollmann et al., 2014, Kim et al., 2018). Costa et al. (2017) introduced an AR prototype to facilitate design processes, where users can add virtual building components to a physical architectural model. A spatial relationship between virtual building components and physical models is established, which provides an intuitive understanding to designers (Carozza et al., 2014). In this review, 15 of 40 articles propose prototypes based on the object-based feature. The most popular use case of this feature includes site progress management (Zollmann et al., 2014, Meza et al., 2014, Mani et al., 2009, Jiao et al., 2013)and discrepancy inspection (Mirshokraei et al., 2019, Georgel et al., 2007, Shin and Dunston, 2009, Zhou et al., 2017, Kumar et al., 2019).

Regarding spatial information, this review identifies two types of information: directions and positions. Kim et al. (2017) used an AR device to display directional information, which points out the direction of hazards. A directional sign informs users where a potential risk could come from, therefore, enhancing safety awareness. Positioning means that AR applications can tell users where an object should be placed in the real world. DaValle and Azhar (2018) used AR to superimpose electrical conduits and plumbing pipes onto wall frames. Benefiting from this, workers can know the precise positions on site to install the conduits and pipes. Similarly, Degani et al. (2019) proposed an AR application to project an interior plan drawing onto the relevant floor. Therefore, users can intuitively tell the room's layout. In addition to indicating positions in the real world, AR can also show the spatial relationship within virtual objects. This can assist in assembly tasks because AR applications can demonstrate assembly processes by assembling virtual objects (Kontovourkis et al., 2019, Bhatt et al., 2017, Hou et al., 2015). In this review, 9 of 40 articles show AR prototypes featured spatial information. The most popular construction activities supported by this feature are assembly (Bhatt et al., 2017, Degani et al., 2019, Kwiatek et al., 2019, Kontovourkis et al., 2019, Hou et al., 2015).

It is also popular to use AR for 2D illustration (e.g., images or text) so the users can directly access information within their sight. Yeh et al. (2012) proposed an AR prototype to project 2D drawings onto plain surfaces so that inspectors can easily view drawings anytime on site. Similarly, Dai et al. (2021) proposed an AR-based communication method for safety inspectors. Safety inspectors can access safety manuals through AR devices on site. Also, Kim et al. (2018) used an AR application to display construction schedules when as-planned models are aligned to as-built site images. In this review, 7 of 40 articles demonstrate AR prototypes designed to deliver 2D illustrations. This function usually collaborates with the background-based (Garbett et al., 2021)or object-based (Mirshokraei et al., 2019) feature to enhance the interaction of the prototypes.

3.2 Displays

This review classifies the display devices of AR into four categories: head-mounted displays (HMDs), computer monitors, projectors, and mobile devices (e.g., smartphones and tablets). Eight articles choose HMDs as the display device of their prototypes. All HMDs mentioned in these articles are Microsoft HoloLens. Users can use their hands to assemble building components (Kontovourkis et al., 2019) or operate heavy equipment virtually via a controller (Kim et al., 2012) while wearing HMDs. Thanks to the wireless solution provided by Microsoft HoloLens, users can move freely (DaValle and Azhar, 2018). Sixteen articles use a computer monitor to view virtual content. One primary reason for using computers as an AR platform is that computers provide better computing performance when dealing with a high volume of data. For instance, Kumar et al. (2019) introduced a registration method based on point clouds. Therefore, a high-spec computer was necessary for the AR platform. Twelve articles introduce smartphones or tablets as the platform to deliver AR applications. Zollmann et al. (2014) argued that mobile devices such as smartphones are more suitable for outdoor activities. Lastly, four articles introduce projection-based AR applications. Projectors were used to project 2D illustrations onto walls or floors.

In addition to different types of display devices, this review also identifies two types of display modes: fixed-pose and real-time displays. Fixed-pose displays mean that the registration of virtual content is static and retrospective, which relies on images or videos captured by fixed-pose cameras as the background of virtual content. Virtual content can be updated when a camera captures a new image or video. In contrast, the registration process of real-time displays is dynamic, and tracking and registration take place synchronously in real time. Prototypes that used HoloLens or mobile devices are all real-time displays. Three of four projection-based prototypes are fixed-pose displays. The other one is real-time because a depth sensor was equipped with a projector (Degani et al., 2019). Most prototypes using computer monitors are fixed-pose displays. Only two articles proposed prototypes based on real-time displays with computer monitors. The porotypes can live stream videos to monitors and superimpose virtual content to videos (Kumar et al., 2019, Shin and Dunston, 2009).

3.3 Tracking methods

This review discovers four tracking methods: sensor-based, vision-based, location-based, and hybrid. Sensor-based tracking techniques track the user’s movement or position through magnetic, inertia and odometer sensors. Also, two or more sensors can be combined to track objects, which is called sensor fusion (Zhou et al., 2008). Vision-based tracking techniques use real-world images and calculate the camera pose through computer vision. There are two types of vision-based tracking techniques: marker-based and markerless-based. In addition, location-based tracking obtains a user's location via the Global Navigation Satellite System (GNSS) or users defining their locations. Lastly, Hybrid tracking techniques combine sensing technologies with computer vision methods (Zhou et al., 2008). For example, the gyroscope can measure the rotation of the camera pose, and the measurement result can be used to enhance the accuracy of the computer vision technique and accelerate the processing time.

Eight prototypes are sensor-based AR. LiDAR is the most common technique in this case. Only one prototype utilised RFID for tracking due to the demand for accuracy (Schweigkofler et al., 2018). Moreover, this prototype was designed for indoor use. Therefore, RFID is more suitable. Seventeen prototypes used vision-based tracking. Ten prototypes use markers to estimate camera pose, while the rest are markerless. Markerless tracking requires computer vision techniques. For instance, Mani et al. (2009) used scale-invariant feature transform (SIFT) to detect and match the key points from site photographs and then used structure from motion (SfM) to estimate camera pose.

Seven prototypes used location-based tracking. GPS was used to track a user's location. Meanwhile, the built-in gyroscope of AR devices tells the orientation of a user's view (Fenais et al., 2019, Behzadan and Kamat, 2008). Another type of location-based tracking utilises the position viewpoint (Tavares et al., 2019). If the viewpoint is a fixed-pose camera, the spatial relations between the camera and real-world objects can be calculated via coordinates. Also, if a user uses a mobile device, their standing position can be incorporated into AR by inputting their coordinates (Yeh et al., 2012, Wang et al., 2022).

One article proposed a hybrid method for tracking (Zhang et al., 2021). The authors used simultaneous localisation and mapping (SLAM) to track the orientation of a user's view and GPS to locate the user's position (Zhang et al., 2021). Seven articles did not describe their tracking methods.

3.4 Impacts on Productivity

This section discusses the construction activities supported by AR applications and their impacts on productivity. Eight types of construction activities supported by AR applications have been discovered (Table 1). AR applications are mostly investigated in two construction activities: progress management and design review. These two activities do not rely on the precise alignment of virtual and real objects since current AR technologies may not provide precise registration and positions. Positioning and layout tasks require an extremely precise overlay of virtual objects. Therefore, it could be the reason that few studies have focused on them. Eleven articles demonstrated experiments to test the impact on construction productivity. These experiments tested three construction activities: progress management, discrepancy check and. These experiments measured labour time, cognitive load, and accuracy to study the impact of AR applications on productivity.

Table 1. Number of articles on classified construction activities

Construction activity	Description	Number of articles
Progress management*	The as-planed model is superimposed over the as-built building.	9
Design review	AR provide an intuitive understanding and collaborative platforms for designers to review their design.	9
Discrepancy check*	AR replaces the traditional error measurement method by overlaying the model to the correct position.	6
Planning simulation	Users simulate the construction process in the real world before starting construction.	6
Assembly*	AR supports the pipes and structural components assembly tasks.	5
Hazard notice	The potential Hazzard source is highlighted, enhancing workers' awareness of the hazard.	3
Positioning	AR facility structural components fabrication by displaying the welding place on the component.	1
Layout	AR presents the layout by projecting the 2D drawing on the floor or wall.	1
* The impacts of AR applications on productivity have been investigated		

Experiments of assembly tasks were usually designed to measure the time taken to accomplish an assembly task. Kwiatek et al. (2019) found that AR can reduce the time for workers with low experience to understand design information. The test result showed that the application reduced the time required to absorb design information by 50%. Furthermore, the assembly facilitated by AR is more accurate than conventional 2D drawings. Hou et al. (2015) tested the cognitive load of workers carrying assembly tasks. They conducted questionnaires for each participant and found that AR can significantly reduce the mental load. Shouman et al. (2021) analysed the impact of AR on enhancing interpretation and collaboration in the design phase based on the result of a survey. Compared to the conventional 2D sketching approach, AR-based design had a significant impact on design interpretation. Sangiorgio et al. (2021) conducted an experiment showing that AR can reduce the decision-making process time and improve efficiency at the design stage. The authors compared the AR-based decision-making approach with the Analytic Hierarchy Process approach and discovered that the AR approach reduced the time by 77% when deciding the panel material. Shin and Dunston (2009) designed an experiment to test the accuracy of anchor bolt offset measurement and measure inspection time. The result showed that utilising AR can shorten the setup and work time by 85% compared to a conventional method using a high-precision survey instrument. However, accuracy was slightly lower than conventional methods. The rest of the 29 articles did not investigate the impact of AR on construction productivity. They showed experiments to only test the performance of their prototypes.

4 Conclusion

This literature review studies AR applications in the construction industry. It reviews 40 articles that cover AR applications in the plan, design and construction phases. All proposed prototypes are analysed based on AR features and applied construction activities. This review reveals the technical details of these AR applications. This review demonstrates different AR features and analyses the use cases for different construction activities. The result shows that positioning and layout tasks are barely studied. Moreover, most proposed prototypes assist the assembly task by delivering step-by-step instructions. Few prototypes identify the assembly components' position in the real world. However, installation works on the construction site require the worker to place the assembly components in the specified position. More research in AR to assist the assembly task should consider showing the components' position in the real world.

Most proposed AR prototypes use vision-based tracking techniques. Hybrid tracking techniques can provide more robust tracking than vision-based tracking. Therefore, further research could adopt hybrid tracking techniques, such as integrating computer vision and sensors to develop prototypes.

This review investigates the impact of AR on the productivity of construction activities. Factors such as time, accuracy and cognitive load have been measured in experiments. To achieve the full industrial adoption of AR and utilise AR to improve productivity, more efforts are required to explore the impact on human factors such as mobility and safety issues. For example, the virtual content may block their vision to the extent that they cannot notice potential risks on the construction site. Besides, it is recommended that more studies should be conducted to assess productivity factors systematically in a single construction task.

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