The Renaissance of Augmented Reality in Construction: History, Present Status, and Future Directions

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Abstract:

Purpose: Augmented Reality (AR) has become one of the most promising technologies in construction since it can seamlessly connect the physical construction environment and virtual contents. In view of the recent research efforts, this study attempts to summarize the latest research achievements and inform future development of AR in construction.

Design/methodology/approach: The review was conducted in three steps. First, a keyword search was adopted, and 546 papers were found from Scopus and Web of Science. Secondly, each paper was screened based on the selection criteria, and a final set of 69 papers was obtained. Thirdly, specific AR applications and the associated technical details were extracted from the 69 papers for further analysis.

Findings: The review shows that: (1) design assessment, process monitoring, and maintenance management and operation were the most frequently cited AR applications in the design, construction, and operation stages, respectively; (2) information browser and tangible interaction were more frequently adopted than collaborative interaction and hybrid interaction;

and (3) AR has been integrated with BIM, computer vision, and cloud computing for enhanced functions.

Originality/value: The contributions of this study to the body of knowledge are twofold. First, this study extends the understanding of AR applications in the construction setting. Second, this study identifies possible improvements in the design and development of AR systems in order to leverage their benefits to construction.

Keywords: augmented reality; construction management; physical environment; virtual content; interaction; review

1. Introduction

Modern construction management in its broader sense is to make informed decisions according to a wealth of information. Perhaps since the emergence of modern construction management, the serious disconnection between the physical environment and virtual information has become an intrinsic part of managerial problems in construction projects (Chen et al., 2015). The problem has further escalated throughout the 2000-2010s and enlarged by the increasing complexity in construction projects. In response, the industry started to embrace advanced digital technologies in order to make accurate information readily available to both managers and workers (Newman et al., 2020). Against this backdrop, Augmented Reality (AR), among all digital technologies, has received attention from both researchers and practitioners in construction.

AR creates a composite view of the virtual and reality by superimposing the digital representations (e.g., image or model) of objects onto the physical environment (Azuma, 1997). Such alignment of digital representations with people's view of the real world enables the interpretation of both the virtual and reality simultaneously. By doing this, AR could improve the information perception process and thereby greatly facilitate decision-making. Researchers have recognized that AR can support operational and managerial activities in various industries (Henderson and Feiner, 2010). In construction, AR has many applications such as the communication of design and planning ideas (Wang et al., 2014b), on-site information retrieval (Yeh et al., 2012), and visualization of facility information for operation and maintenance (Baek et al., 2019).

Given the existing research efforts, a literature review becomes necessary to evaluate existing knowledge and uncover supplementary directions for future studies (Webster and Watson, 2002). Some researchers subscribing to this point have reviewed the literature of AR in construction. Chi et al. (2013) reviewed 101 studies before 2012, with a focus on technologies influencing the development of AR applications (e.g., localization and user interface). Rankohi and Waugh (2013) reviewed the relevant literature as of 2012 to discover facts about the stage, sector, scope, and devices of AR applications. Wang et al. (2013) reviewed articles published between 2005 and 2011 and found that no article introduced the industrial adoption of AR in construction. Behzadan et al. (2015) investigated challenges faced by AR visualization in infrastructure projects and provided solutions correspondingly. Recent years also see some review articles regarding AR in construction, but nearly all of them focused on a few specific perspectives. For instance, Li et al. (2018) and Moore and Gheisari (2019) reviewed the AR literature solely on construction safety management. Calderon-Hernandez and Brioso (2018) reviewed 48 papers regarding the simultaneous use of BIM and AR in the design and construction stages. Elghaish et al. (2020) reviewed the use of immersive technologies (including AR) and drones to support digital transformation in construction.

In view of the ever-updating technologies today, this paper attempts to uncover the recent development and implementation of AR systems from the construction literature published after 2012. Three specific objectives will be addressed:

1. To revisit the research and development trends of AR systems in the construction setting;

2. To synthesize how AR systems receive and react to users' input, and how they present information to users; and

3. To identify how AR has been integrated with other technologies in construction.

2. Overview of Augmented Reality

As a concept of providing the digitally interactive experience, AR is not new. Dating back to 1901, Frank Baum, an American author, mentioned an electronic spectacle named as "character marker" that enabled overlaps of data and real life. Decades later in the 1950s and 1960s, the concept of AR was firstly made true - such as "Sensorama" and "head-mounted display" - by scientists from different disciplines. Attributed to the fast development of technologies, today, when people talk about AR, they are mainly referring to AR systems. A typical AR system must have three main features (Azuma, 1997). First, it must enable interactions between the physical and virtual contents. Secondly, it enables the real-time overlay of virtual contents onto the real world. Thirdly, it should be registered in three dimensions. The realization of these features requires the use of various techniques, including tracking techniques, display techniques, and interaction techniques. By using these technologies, AR can enhance people's interpretation of the real world (van Krevelen and Poelman, 2010).

Tracking techniques are used to log and verify the position and orientation of users, and thus play important role in the alignment and registration of virtual contents onto the physical environment (Azuma et al., 2001). Depending on the specific application scenarios, different types of tracking techniques can be adopted. For example, sensor-based and vision-based methods generally verify the position and orientation by using various sensors (e.g., magnetic, acoustic, and mechanical) and image processing methods, respectively. In addition, hybrid tracking techniques are becoming increasingly popular for AR applications in many different fields. A hybrid tracking technique takes advantage of both sensing and computer vision techniques, which can generate a more robust estimation of user's position and orientation than using one single type of technique (Zhou et al., 2008).

Display techniques combine virtual contents and real-world environment and show both simultaneously. Three types of display techniques are widely adopted, namely the handheld display, the head-mounted display, and the projection-based display. The handheld display employs mobile devices like a smartphone or a tablet (Wagner and Schmalstieg, 2003). These mobile devices use video-see through methods, providing users with a video view of the physical environment that is augmented by the corresponding virtual contents. The head-mounted display is worn on the user's head and can be a part of a helmet. Apart from video-see through methods, the head-mounted display can use optical see-through methods that allow users to view the real-world environment with their eyes and let them see the overlaid virtual contents by holographic optical elements or half-silvered mirrors. Compared with the video-see through methods, one major benefit of optical see-through methods is that they can create a superior presentation of the physical environment (Zhou et al., 2008). The projection-based display, also called the spatial display, does not require users to equip any devices, leading to minimal intrusiveness. Projection-based displays directly show the virtual contents on the surfaces of real-life objects and can naturally scale up to enable collaboration between a group of people (Tonn et al., 2008).

Interaction techniques concern creating appropriate intuitive interactions between users and AR systems, and can be classified as information browser, tangible interaction, collaborative interaction, and hybrid interaction (Billinghurst et al., 2015). Information browser refers to the most basic and straightforward interaction that views the visualized AR scene and browses the information provided. For tangible interaction, objects in the real-world environment could be deployed as the elements of the AR interface. For example, Kato et al. (2000) proposed an AR application, in which the user can use a real paddle to select and place the virtual objects in a living room environment. Collaborative interaction is designed and developed for either co-located or face-to-face collaboration, both can improve physical collaborative workspaces (Billinghurst and Kato, 2002). Multiple users in different roles can use different display devices to look at the same object but be presented with different AR experiences that are tailored to their needs. Hybrid interaction combines complementary interfaces and allows users to interact with AR systems through various types of input such as gesture and speech (Zhou et al., 2008).

The diversity in these three types of techniques produces many different types of AR systems for corresponding application scenarios. Throughout a construction project life-cycle, many operational and managerial tasks require enough information to interpret their complex relations to the physical environment and objects (Shin and Dunston, 2008). Both commercial and tailor-made AR systems have been adopted by different stakeholders in order to meet their requirements of integrating the real world and virtual information, but there still remains much room for further improvements (Wang et al., 2013). The understanding of extant efforts thus is necessary before possible improvements can be made to leverage the benefits of AR to construction.

3. Research methods

The review presented in this paper was carried out in three steps that have also been adopted in many existing review studies (e.g., Chen et al., 2015; Mok et al., 2015). The first step is to search the literature exhaustively. The databases for searching are Web of Science (WoS) and Scopus. WoS core collection covers more than 21,100 high-quality journals (Clarivate

Analytics, 2019), and Scopus contains more than 23,452 journals with over 610 journals under the fields of 'architecture', 'construction and building', and 'civil and structural engineering' (Elsevier, 2020). Searching both databases guarantees full coverage for the relevant literature and thereby makes it possible to draw broad conclusions (He et al., 2017). The literature search was conducted on 30th December 2019, using the query combination '(augmented reality) AND (building OR construction OR civil OR infrastructure)', i.e., the retrieved papers should explicitly mention AR and a construction term. In addition, the review only considered peer-reviewed journal papers since they tend to be more rigorous and mature than other types of literature (Jesson et al., 2011), and the language of the paper was limited to 'English'. Following these rules, a total of 546 papers published from 2013 to 2019 were collected initially.

The screening of the title and keywords of the collected papers found that many of them did not fit the review objectives. This is unsurprising because either building, construction, or civil are general terms. Therefore, in the second step, one author filtered suitable literature according to three criteria: (1) papers in areas irrelevant to construction, e.g., manufacturing and surgery, were excluded; (2) papers not providing sufficient technical details of AR systems were excluded; (3) papers only discussing the application potentials of AR without evaluation (either in the laboratory or actual field) were excluded. Then, another author double-checked the selected papers to decrease potential bias. Disparities were addressed by further discussions until a joint agreement about the inclusion or exclusion of involved papers arrived. After filtering, 69 papers were finally obtained for further analysis.

In the third step, the authors carefully read each paper and manually extract descriptive information, namely, year of publication, project stage(s), and AR application(s). More importantly, attention has been paid to the interaction between human and AR systems and the integration of AR with other technologies.

4. Results

This section begins with an overall description of the literature (Section 4.1). Next, it presents what the recent AR applications in construction are (Section 4.2), how users control the AR systems and how the AR systems present information to users (Section 4.3), and whether AR has been integrated with other technologies to leverage its full potential to construction (Section 4.4).

4.1. General descriptions of the literature

As shown in Figure 1, the 69 papers came from 28 journals, and the top two journals were *Automation in Construction* and *Journal of Computing in Civil Engineering*. Grouped into "Others" were journals that published only one relevant paper each.

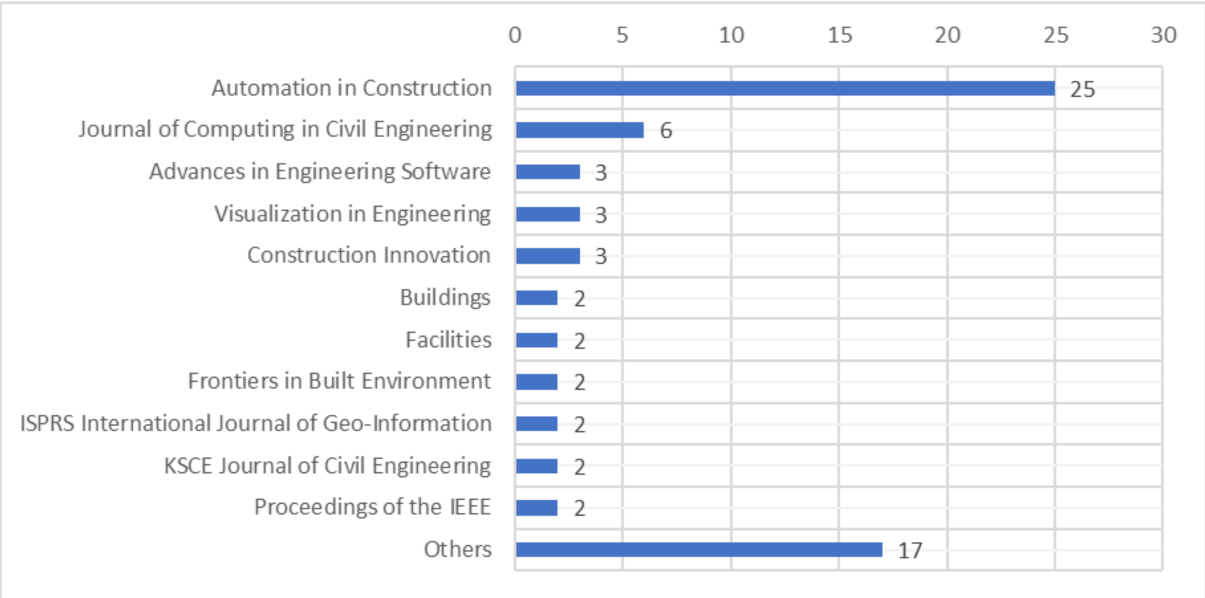

Figure 1. Sources of the 69 papers

Figure 2 shows the distribution of papers published between 2013 and 2019. Overall, the number of papers continuously dropped since 2013, reaching its bottom of three in 2016 and then bounced up in 2017. This U-shape curve could reveal a renaissance of AR research in construction, which might be attributable to the increasingly mature AR technologies in recent years (Gartner, 2018). A further investigation in the authors of the reviewed papers found that Wang X., Kamat V.R., and Ayer S.K. were three notable researchers who published more than five papers about AR in construction between 2013 and 2019. Moreover, 26.67% of the studies published between 2017-2019 have the same author (at least one) of the studies between 2013-2016. Such a result indicates that efforts in exploring the AR applications in construction are coming from different researchers or research groups.

Figure 2 also shows the number of papers concerning different project stages. Findings can be drawn by integrating Figure 2 and the results of Wang et al. (2013) and Rankohi and Waugh (2013). In studies published before 2013, most of them used AR in the construction stage; less in the operation stage. In studies published from 2013 to 2019, over half of them focused on the construction stage, and the number of studies focusing on the operation stage has become nearly two times as compared to the number of studies focusing on the design stage. These figures indicate that the construction stage is still taking the leading position to embrace AR, and the applicability of AR to project operation has been increasingly recognized.

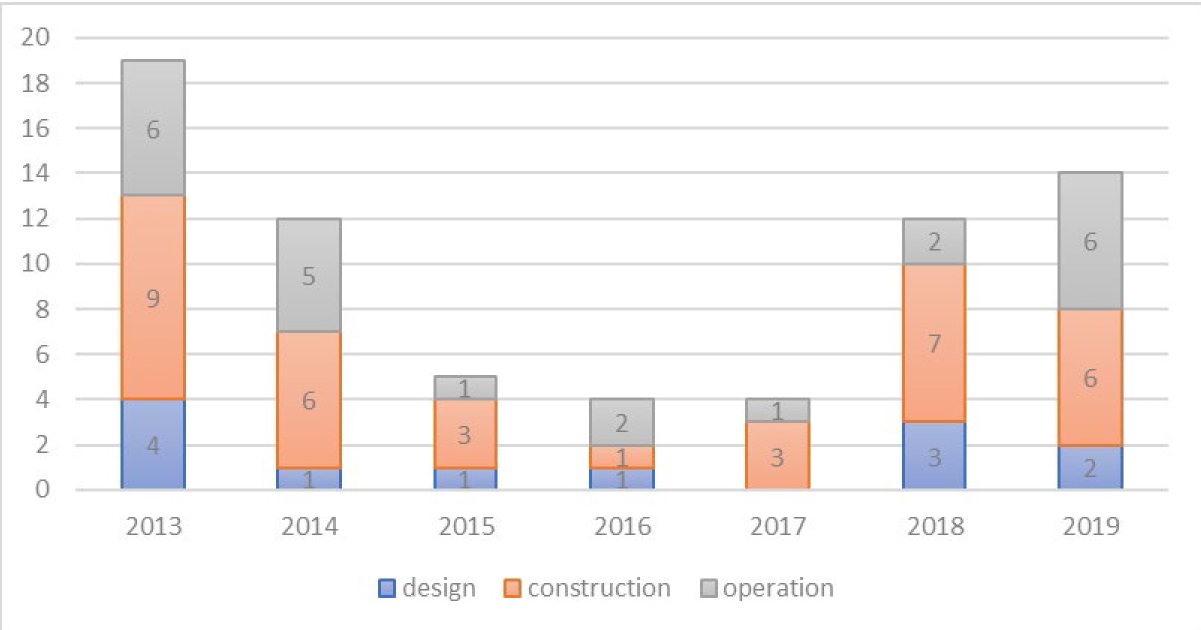

Figure 2. Number of publications from 2013 to 2019 (by project stage)

4.2. AR applications in construction

Figure 3 shows the specific applications of AR in different project stages. Based on authors' experience and relevant studies, various AR applications are grouped into three categories for the design stage, and seven and six categories for the construction and operation stages respectively. One may notice that several studies consider more than one application, and the comparison of studies published before and after 2013 reveals that AR applications in construction have become more diverse. In the design stage, AR has been popularly used for assessing the designed drawings or models in the physical environment and communicating design ideas to different stakeholders (Alsafouri and Ayer, 2019). In the construction stage, progress monitoring, assembly instruction, and quality management were dominant AR applications. This is consistent with the findings of Rankohi and Waugh (2013) and Wang et al. (2013). However, research efforts have also been focusing on safety management, positioning, and other applications, which were not widely investigated by studies published before 2013. In the operation stage, maintenance management and operation was the main AR application. This is because maintenance is one of the major tasks in the operation stage, which requires a great amount of information to be available in-situ (Hou et al., 2014). AR can seamlessly connect the physical facilities with their corresponding virtual information, facilitating instant and informed decision making (Dong et al., 2013). By providing additional context information, AR has also been used for disaster management and emergency response, localization and navigation, and energy management (e.g., Golparvar-Fard and Ham, 2014; Tsai and Yau, 2014).

Acknowledging the rising diversity of AR applications in construction, it is noticeable that some AR applications are becoming more mature for actual projects. Jiao et al (2013) implemented AR for monitoring the construction progress of the Shanghai Center. Zhou et al. (2017) used AR to support quality management in a metro construction project in China. Nevertheless, most of the AR applications in the operation stage are still under lab experiments. In addition, applications such as personnel management and cost control wait for further exploration.

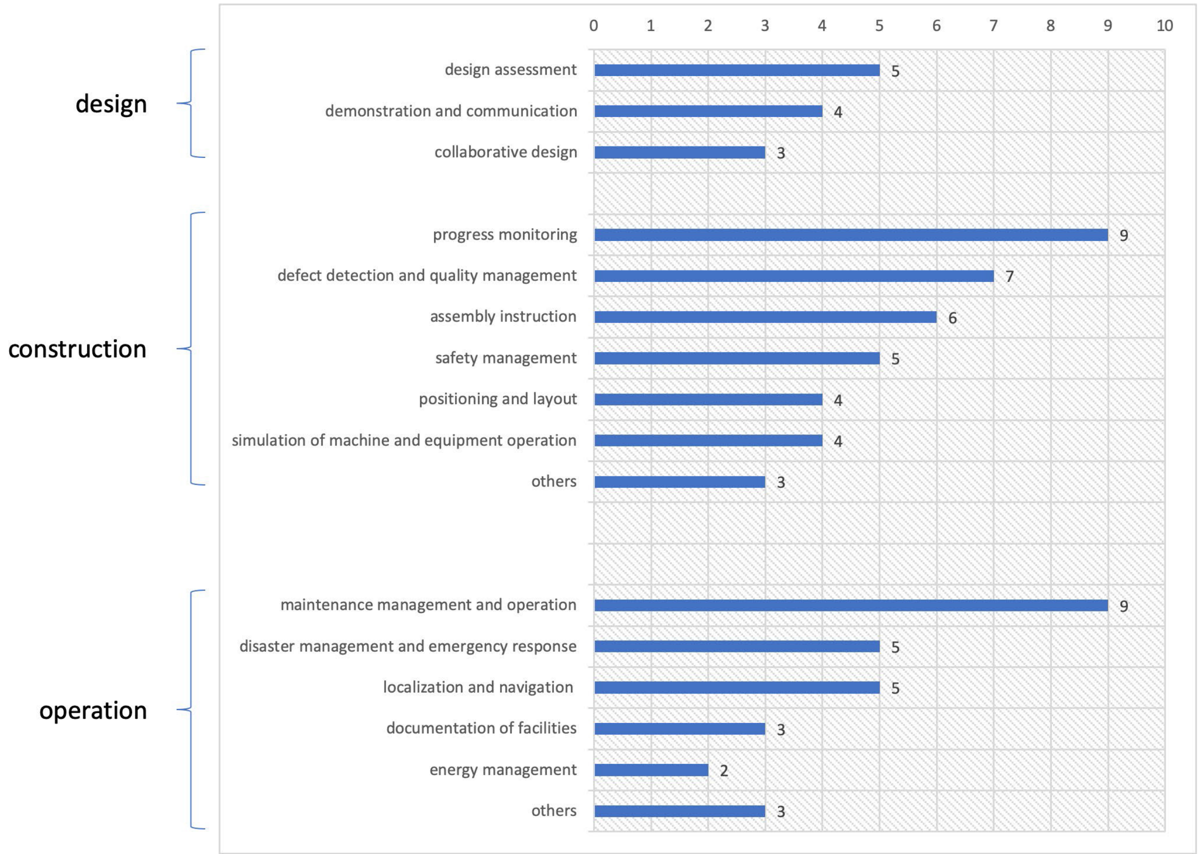

Figure 3. Number of publications by target application

4.3. Interaction between users and AR systems

Based on the extracted data, a Sankey chart was drawn to summarize the AR-user interactions in construction. The Sankey chart provides a graphical presentation, in which the width of the series can clearly indicate the number of studies that mentioned the diverse options of how users control the AR systems and how the AR systems present on-demand information to users (see Figure 4). Over 65% of the reviewed studies adopted the handheld display, while the head-mounted display is also a relatively popular choice. In contrast, the projection-based display has not been widely used in construction. A possible explanation could be the difficulties in setting up the projector and the projected texture might not be sufficiently bright or visible in a complex construction environment.

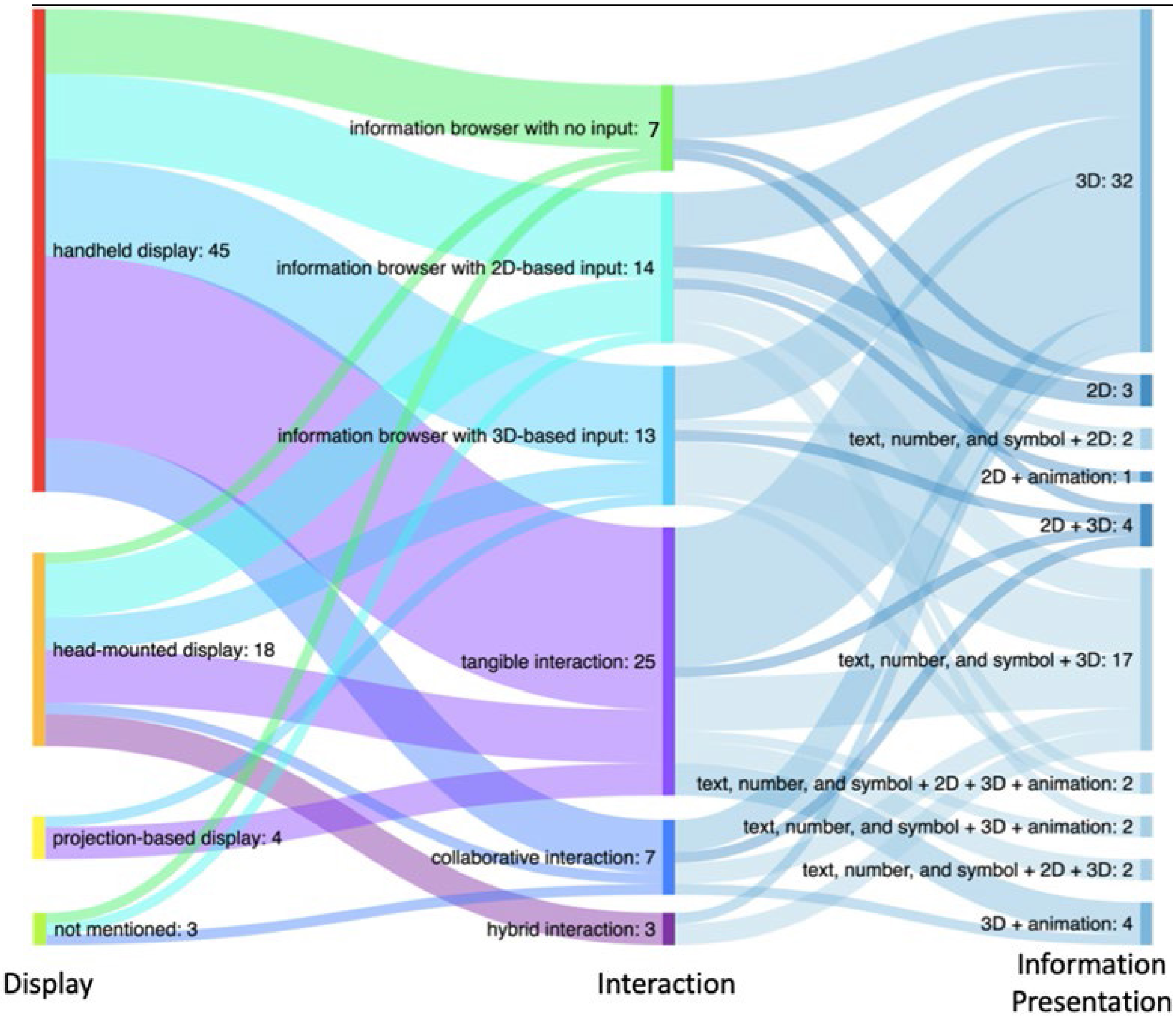

Figure 4. Overview of AR-user interactions (The total number of display is larger than 69 because one paper used two types of displays)

Information browser dominates the interaction between users and AR systems in construction. 14 studies used 2D-based input, and 13 studies used 3D-based input. 2D-based input provides simple interaction, and thus are relatively easy to operate. In the AR system developed by Espíndola et al. (2013), users were allowed to click the buttons or use the keyboard to change their view. Other types of 2D-based interactions mentioned in the reviewed studies include: (1) filtering the information to view; (2) navigating into details of virtual contents; and (3) modifying the visualization style and format. These kinds of 2D-based interactions could also be easily performed using traditional input devices (e.g., keyboard and touchpad). 3D-based input benefits users by interacting with virtual construction components and resources in a natural way. The input devices allow six degrees of freedom (DOF) manipulation (e.g., translation and rotation in 3D) of virtual objects. Like 2D-based input, 3D-based input supports information filtering and other functions. For instance, Soria et al. (2018) developed an AR system for the management of underground facilities. In this system, users can rotate the digital 3D model by swiping left and right and can also delete the model from both the view and the database.

Following the information browser, tangible interaction has been adopted in 25 studies. Tangible interaction is increasingly preferred in construction because it allows users to interact with virtual contents by manipulating physical objects. This is attractive to construction since stakeholders often require real-time information tied to dynamically changed objects and locations (Chen and Lu, 2019). Thanks to the advances in AR devices, tangible interaction can be more effectively deployed. For example, the Google Tango tablet used by Ratajczak et al. (2019) was equipped with a time-of-flight (ToF) camera and an IR projector, both can help to accurately measure the position of the Google Tango tablet with respect to its surrounding environment. This type of mobile AR device can generate the 3D point clouds of physical objects in a real-time manner, which can be further processed to obtain details of these objects and link the generated information to them through AR systems.

The review study conducted by Wang et al. (2013) showed that multidisciplinary collaboration would be one of the trends for AR applications in construction. In the reviewed 69 studies, seven of them deployed collaborative interaction and suggested that this kind of interaction is suitable for information communication and exchange in construction. For instance, the engineers can make annotations about existing cables and pipes overlaid with AR visualizations, and the technicians can know the locations and other information of these cables and pipes before they determine whether extra pipes and cables are required (Olbrich et al., 2013). Hybrid interaction is also encouraged by many previous studies since it is more adaptive to the changing environment and can relieve users from screen input or external devices (e.g., mouse, keyboard, and touchpad). However, only three recent studies reported success cases of hybrid interaction in construction. In these studies, users were asked to wear the head-mounted device (i.e., Microsoft HoloLens) and interact with the virtual contents by their gestures (Baek et al., 2019; Mascareñas et al., 2019). Despite the diverse interaction mechanisms, no study has used speech or eye movement as inputs for intuitive interaction, leaving a possibility for further investigation.

4.4. Integration of AR and other technologies

The technical details of the reviewed studies allowed the authors to analyze whether the AR systems were used alone or in conjunction with other technologies. A notable trend is that many recent research works have integrated AR with building information modeling (33 papers), computer vision (22 papers), and cloud computing (12 papers). As shown in Figure 5, three papers even integrated AR with all these three technologies to leverage the benefits of AR to construction. Nevertheless, other technologies such as Auto-ID were only mentioned in very few papers and thus were omitted in the following investigations.

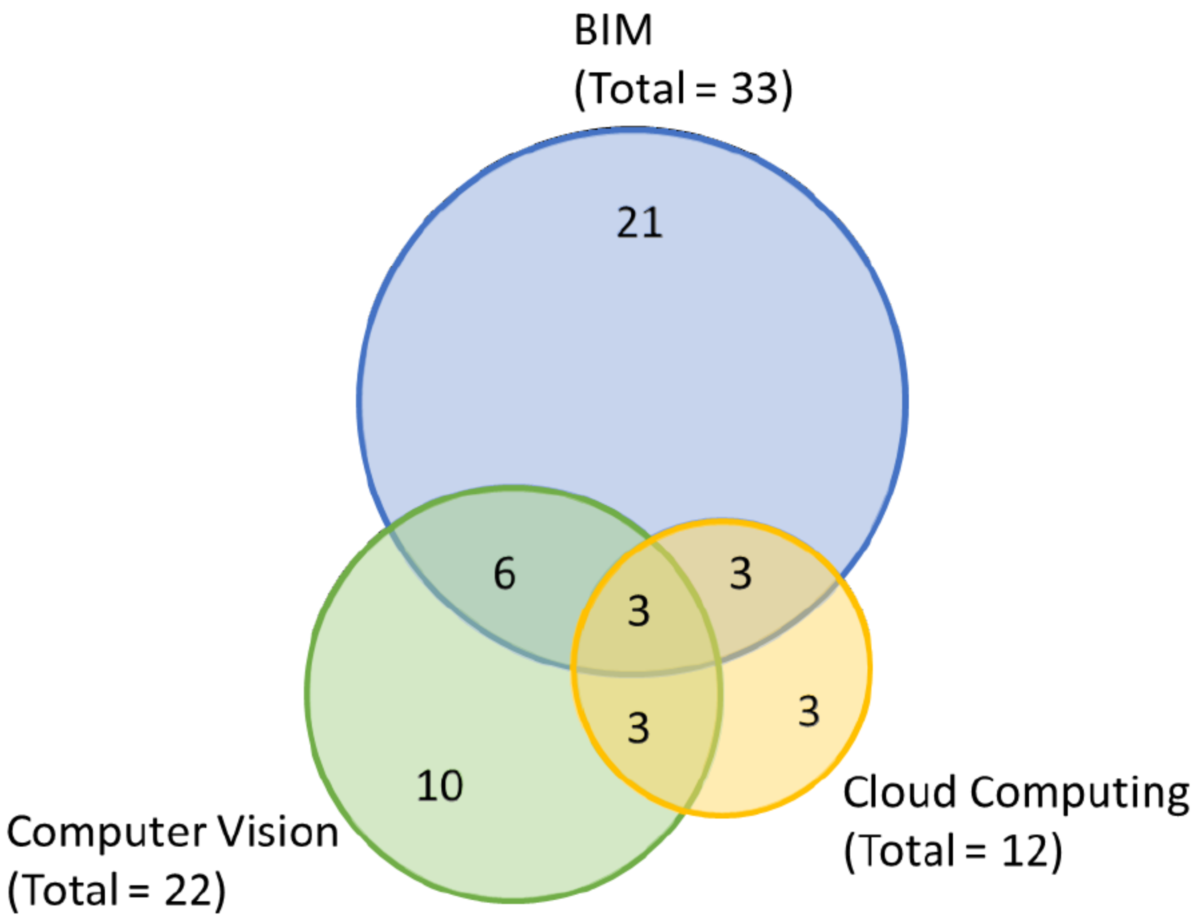

Figure 5. Number of publications integrating AR with BIM, computer vision and cloud computing

4.4.1. Building information modeling

Throughout the life-cycle of a construction project, the delivery of many operational and management tasks could be improved if the corresponding workers and managers can access to not only the geometric information (e.g., size, shape, etc.) but also the non-geometric information (e.g., material, function, etc.) of construction elements (Jalal et al., 2020). In these cases, the integration of BIM and AR provided an ideal solution to meet such need, through which advantages of BIM and AR to construction were further leveraged. A BIM model is basically a digital model that contains the physical and functional details of a building. AR can superimpose the BIM model onto the physical project. The merge of the as-designed BIM model and real-world environment provides a vivid presentation of geometric information for operational and managerial tasks. Wang et al. (2014a) presented the BIM model in a handheld AR device to guide on-site assembly tasks. The comparison between the as-designed BIM and the as-built situation can significantly ease the progress monitoring. Zhou et al. (2017) used AR and BIM to measure the segment displacement for quality management in tunneling construction. They treated the BIM model as the baseline model and compared this model with actual video through an image-matching program. Likewise, Kwon et al. (2014) used an AR system to match the shape information of BIM objects and images taken on the construction site, and the matching results can support defect detection.

Apart from the geometric information, some of the reviewed studies used AR to make non-geometric information readily available on site. This is extremely helpful for supporting complex construction tasks. For example, Chen et al. (2016) integrated BIM into the AR system so that the material information, rigging orders, and construction schedules can be automatically fetched from BIM and augmented as a layer of information over the real-world view of workers. Ratajczak et al. (2019) also suggested that the integration of BIM and AR could provide context-specific information on tasks and relevant building components, and thus enhance the quality of construction works. Regarding maintenance, some examples can be found in Irizarry et al. (2014) and Soria et al. (2018) that integrated BIM and AR to facilitate maintenance and repair operations for buildings and infrastructures. Their proposed systems can simplify the information retrieval process, and facility managers and maintenance workers can have the condition of a facility, maintenance requirements, and all other information they needed for maintenance.

4.4.2. Computer vision

In its simplest definition, CV refers to training computers to generate and interpret explicit information from images or videos (Ballard and Brown, 1982). CV has remarkably changed the traditional construction management by enabling automatic activity recognition, object tracking, and performance monitoring (Sherafat et al., 2020). The advances in CV technologies and algorithms have also made them extremely suitable for AR applications since they can make use of the images or videos taken by the built-in camera of an AR device to provide functions such as visual tracking and registration.

CV technologies can benefit AR by facilitating both marker-based and marker-less tracking and registration. Chi et al. (2013) found that marker-based tracking and registration methods were generally adopted in studies published before 2013 but suggested that marker-less methods should be more suitable for construction fields. However, among the reviewed 69 studies, marker-based methods were still used more frequently than marker-less methods. Regular markers can be placed at different locations that are suitable for various construction and operation activities (Portalés et al., 2018). When a marker is recognized, the AR device would display the virtual content relevant to the location of the marker in space. Researchers have also attempted to improve the marker-based tracking and registration methods so that they can be applied to different scenarios. Ahn et al. (2019) proposed a two-step method, including image segmentation for filtering out the markers and object detection for estimating the coordinates, to perform geometric transformation for projection-based display. Mascareñas et al. (2019) adopted various types of markers (e.g., barcode, QR code) in order to cope with the common occurrence of facilities in nuclear infrastructure. Although marker-based methods are relatively straightforward to use, they require markers being placed at suitable locations without any occlusions.

The use of CV for marker-less tracking and registration relies on algorithms for extracting features of the scenes and identifying the location and position of AR devices in the real-world coordination system. Depending on the target scenes and their associated features, different feature detectors and descriptors have been adopted in the reviewed studies. Examples include the Speed Up Robust Features (SURF) used in Kim et al. (2018), and the Canny edge detector used in Fazel and Izadi (2018). In addition, deep learning is expected to significantly improve the marker-less tracking and registration for AR applications. For instance, the convolutional neural network – a typical class of deep learning algorithms – has been demonstrated useful for location tracking in AR-based facility management (Baek et al., 2019). Marker-less methods do not need pre-installed markers and can provide accurate tracking and registration if robust features are available. However, for a complex, dynamic environment like construction, the use of CV for marker-less tracking and registration is vulnerable to drift and fact motion. In such situations, a hybrid method that combines sensors and CV should be adopted to overcome problems such as drift and occlusions (Hou et al., 2014).

With the tracking and registration enabled by CV, several value-adding AR services have been developed. Bae et al. (2013) used CV to recognize buildings from images taken by the camera of the AR device. Once a target building is recognized, the AR device can query relevant information of that building and show the information to the field personnel for decision making. Kim et al. (2017) proposed an AR-based safety management system in which multiple objects in the images were tracked and their distances were continuously measured. This system allowed managers to timely view the hazard information in an AR device, and make corresponding safety instructions for the sake of risk prevention. Koch et al. (2014) and Baek et al. (2019) used CV to perform indoor localization, based on which location-specific information was represented in the AR device for indoor navigation and maintenance operations. All these examples illustrated the integration of CV and AR can significantly ease the information accessibility for users so that informed decisions can be made in a real-time manner.

4.4.3. Cloud computing

Mobile AR devices are flexible and convenient for on-site personnel to use, but they generally have limited memory and computing capacities for computation- and data-intensive

AR applications. This is extremely serious when AR is integrated with CV and BIM. Mobile AR devices may not be able to run CV algorithms and render the BIM models. Therefore, cloud computing has been used to facilitate the delivery of AR applications.

Cloud computing refers to “a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources that can be rapidly provisioned and released with minimal management effort or service provider interaction” (Mell and Grance, 2011, p.2). In the reviewed studies, the integration of AR and cloud computing has eased information exchange by storing the required information in a centralized cloud platform. Because no information must be stored locally in the memory of an AR device, wasteful duplications of information can be significantly reduced (Chu et al., 2018). This benefit has been recognized in actual practices, Jiao et al. (2013) adopted a cloud-based system to integrate AR and BIM in the 3D web environment and suggested that their proposed system can be dynamically updated and adapted to different usage requirements. Additionally, Hou et al. (2014) linked users to the object-oriented facility information that is stored on a cloud server, and then augmented the information in the AR interface for real-time facility management.

By transferring the data processing workload to the cloud server, cloud computing can relief the AR devices from heavy computational tasks and improve the efficiency of data processing. In the cloud computing-based AR system developed by Olbrich et al. (2013), the AR device was only responsible for simple computational tasks including the image acquisition and visualization of the augmented images, and the cloud server was used to address all other computational tasks such as processing the image and tracking the camera. Kim et al. (2017) used a cloud server to conduct most of the processes, and the AR interface could be synchronized with this cloud server by using HTML. Baek et al. (2019) allocated a computer that had powerful graphics processing units as a cloud computing server in order to ensure a fast deep learning-based localization. Acknowledging the benefits of cloud computing to AR applications, it should be noted that the communication between cloud servers and AR devices requires a stable network, which however might be extremely difficult to guarantee in a dynamic construction site.

5. Future directions

In previous review studies, Chi et al. (2013), Rankohi and Waugh (2013), Wang et al. (2013), and Behzadan et al. (2015) described several research directions of AR in construction, such as expanding the applications of AR from the construction stage to other project stages, the use of mobile AR devices, the integration of AR and cloud computing, human-AR interaction, and context-aware AR. The findings of this study reveal that much research efforts have been devoted to these directions. However, the reviewed papers still highlighted several technical challenges associated with interaction and information processing processes (e.g., Zaher et al., 2018; Chalhoub and Ayer, 2019). Therefore, efforts are needed to further upgrade users' experience of AR in construction. Specifically, four possible future directions of AR in construction are described as follows.

First, natural interactions between users and AR systems are important for streamlining the deployment of AR in construction. The design of natural interaction should ensure that users can easily interact with virtual content without problems such as information overload and attention disruption. In a dynamic construction workspace, if workers hold mobile AR devices or wear head-held AR devices while walking within the construction site, they should not be required to pay much attention to the control of AR devices and cannot be disturbed by the information presented to them in order to avoid safety accidents. Therefore, user-centric interaction design has been advocated since it fully considers how to help users interpret the virtual contents overlaid onto the physical environment (Eitoku et al., 2006). Future studies can explore the user-centric design of human-AR interaction according to the nature of cognition on the user's performance when merging multimodal cues in the real-world environment. Moreover, future studies can propose systematic methods to evaluate the human-AR interaction in construction. Both subjective metrics (e.g., cognitive load and fatigue) and objective metrics (e.g., the time and accuracy of task delivery) should be used to comprehensively measure the effectiveness and efficiency of the control mechanisms and information presentation of AR in various application scenarios.

Secondly, two major issues associated with the integration of BIM and AR have been highlighted. One is related to the reduction of the model complexity and the other one is associated with the communication of BIM information to an AR system, both concerning how the model can be correctly visualized without the loss of essential information. Irizarry et al. (2013) introduced some manual complexity reduction techniques, which include the welding of overlapping vertices, the elimination of unnecessary geometry, and the simplification of mesh. Tools including Vizup and Autodesk 3ds Max have also been used for polygon decimation (Singh and Delhi, 2018). Depending on the platforms for developing the BIM models and AR applications, various data formats and the corresponding format transfer methods have been used for BIM-AR integration. Some of these methods need one time of conversion (e.g., "HOOPS-X3D" in Jiao et al. [2013] and "RVT-IFC+DAE" in [Williams et al., 2015]), and others require a series of conversions (e.g., "IFC-OBJ/MTL-L3D" in [Meža et al., 2014] and "RVT-MAX-FBX-FBX-WT3" in [Chu et al., 2018]). Acknowledging the availability of various methods for different scenarios, it should be noted that a full conversion has hardly been achieved, and manual adjustments of the converted BIM models are often needed. Therefore, more robust conversion methods are expected to be developed and validated in actual projects.

Thirdly, the augmentation of the real and virtual contents should be more compelling for construction stakeholders. When stakeholders conduct construction activities, they often need information about the surrounding environment in addition to the design drawings or other readily-available documents (Tsai, 2014). However, most of the reviewed AR systems treated the physical environment as background, without deriving any semantic information from it for decision making. It is thus expected that, in future AR applications, the information presented to user-ends should not be derived solely from the virtual content, but the semantic understanding of the surrounding environment. A few studies have used computer vision technologies to help AR systems to understand the semantic information of objects in the construction and operation stages, but an extensive database of reality should be developed to make AR responsive to providing context-aware information.

Finally, AR can be integrated with a new computing paradigm – edge computing – to improve the quality of service for computation-intensive applications. Although previous studies have adopted cloud computing to provide such function in construction, the use of cloud computing has been facing challenges such as high latency, resource consumption, and unstable network in construction sites. In contrast, edge computing is a distributed computing paradigm that transfer data processing and analysis close to the edge of data sources or networks (Satyanarayanan, 2017). Advantages of edge computing include shifting the storage and computation load from center to edge, reducing ingress bandwidth into the cloud, enabling a real-time response, reducing latency, and enhancing scalability (Shi et al., 2016). Such advantages make edge computing suitable for the rapid delivery of AR services. In the manufacturing industry, Fernández-Caramés et al. (2018) has integrated AR with edge computing to provide dynamic on-demand information and analyzed the benefits of edge computing over cloud computing. Nevertheless, one cannot simply apply Fernández-Caramés et al. (2018)'s solution to construction since the working environment and application scenarios in the manufacturing and construction are significantly different. Therefore, future studies can focus on how to deploy the edge computing for different scenarios in construction and how to integrate AR and edge computing to enable fast AR device communications for various users in construction projects.

6. Limitations of the review method

Some limitations of the review method should be recognized. In the literature search stage, the construction term used in the search query, e.g., building or construction, is relatively general, which led to the fact that the initial set of collected papers contained many irrelevant studies. Additional search criteria can help to narrow the results but will increase the risk of omitting important references. The combination of database searches and snowballing might be a more suitable method for future review studies. Moreover, the filtering process was done manually in this study by reading the abstracts of all 546 papers. The efficiency of this process, however, can be significantly improved by using advanced text-mining tools such as RobotAnalyst (Przybyła et al., 2018).

7. Conclusions

By taking research work published from 2013 to 2019 as recent advances, this study reviewed 69 journal articles on AR in construction. Several key findings have been drawn from this review. First, a renaissance of AR research in constriction is observed, but most of the reviewed studies still focused on the construction stage. Secondly, design assessment, process monitoring, and maintenance management and operation were the most widely implemented AR applications in the design, construction, and operation stages, respectively. Thirdly, information browser and tangible interaction were the major interaction mechanisms of AR in construction, and hybrid interaction was only enabled by advanced AR systems for a few application scenarios. Fourthly, AR has been integrated with BIM, CV, and cloud computing in order to leverage its benefits to construction. BIM and CV can significantly improve the virtual and physical contents presented to users; cloud computing shares the majority of computation-intensive tasks with AR devices for rapid response in more complex applications.

The review also identifies some unaddressed issues, including natural interactions between users and AR systems, seamless conversion of BIM to AR, merging virtual contents with information obtained from the physical environment, and effective strategies for computation- and data-intensive AR applications. Therefore, four possible directions for future search can be proposed: (1) AR systems should follow a user-centric interaction design so that users can enjoy more intuitive interactions for improved user experience; (2) Development of robust conversion methods for BIM and AR integration; (3) Technical progress in semantic understanding of the physical objects and surrounding environment is expected to unleash the full power of AR to construction; and (4) Future deployment of AR in construction could make use of edge computing which provides the ubiquitous capability of heterogeneous computing for AR applications.

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