

CONTEXTUALIZING BENEFITS AND LIMITATIONS REPORTED FOR AUGMENTED REALITY IN CONSTRUCTION RESEARCH

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SUMMARY: Augmented Reality (AR) has been in use for years, and is increasingly being adopted in the construction industry. Research has explored various applications of AR in construction to identify its benefits and drawbacks. To synthesize these findings, prior works have conducted literature reviews about AR in construction, but these papers generally focus on identifying attributes for which there is consensus about AR benefits or drawbacks. While this is important, it highlights the need to identify trends in AR literature for which there is divergence in reporting to better understand the underlying contextual factors that may impact the success of AR implementation. This paper investigates trends in AR literature by studying both benefits and limitations reported when using current generation AR devices for construction applications. This is done by reviewing 49 articles from 2013 to 2020 found through a key word search for “augmented reality”, “mixed reality” and “construction”. The papers are categorized according to the most common attributes reported. The benefits and limitations identified are analysed based on how the technology was used. For several AR attributes, including ease of implementation, learning/training time, field of view, hardware and software performance, occlusion and immersiveness, there was consensus in reporting among researchers. For other AR attributes, including cost, cognitive performance, development time, tracking and registration, attitude towards the technology, and efficiency, there was divergence in reports among researchers. For each of these divergent attributes, the authors provide a discussion related to the contextual factors that were present. Beyond illustrating that some attributes do not lead to agreement between researchers, the results also indicate contextual factors that may contribute to the difference in reports. These findings contribute to the literature by enabling researchers to include or exclude contextual factors to gain or mitigate previously reported benefits or challenges when using AR in construction.

KEYWORDS: Augmented Reality, Mixed Reality, Construction, Limitations, Advantages

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1. INTRODUCTION

The construction industry is experiencing growth in both developed and developing countries (Deloitte, 2019). It plays an important role in the global economy as it is projected to grow to \$10.5 trillion by 2023, at an annual growth rate of 4.2% from 2018 to 2023 (Wood, 2017). Despite the importance of this sector, researchers have highlighted the construction industry's poor productivity levels, and suggest that it lags behind other industries in terms of efficiency improvements (Bankvall et al., 2010). This recognition of need for improvement has motivated practitioners and researchers to explore and implement emerging technologies that may support performance improvements for this field.

Augmented Reality (AR) has been gaining attention in recent years for supporting the building industry. This technology allows users to view virtual objects overlaid onto their view of the physical environment (Azuma, 1997). This provides an experience where virtual content, including information and graphics, can be presented in their physical context. AR has been explored for many different professional fields, including medical education (Barsom et al., 2016) and military training (Zhu et al., 2015). Furthermore, it has also been implemented in various Architectural (Wang, 2009), Engineering (Menezes et al., 2017), and Construction (Piroozfar et al., 2018)(AEC) applications. Despite the advances of AR in these domains, this field of research is still evolving. As a result, there are various different technological and implementation-related benefits and limitations reported in the literature that may impact the overarching success of AR for construction applications.

Many studies have explored AR and reported limitations in its application for construction tasks. However, the limitations reported are typically specific to the use-cases explored. While this is logical for each individual paper, it is not clear from a cursory review of AR literature which limitations have consensus among the research community and which are unique to individual studies. This makes it difficult for researchers to strategically address technological and implementation limitations that are most broadly impactful in order to maximize the benefit of AR in construction. A better understanding of the trends in limitations that are reported in AR literature can help the research community to better identify specific areas of improvement for this technology and the implementation of it.

This study investigates the most common limitations and benefits reported by construction-related research publications using current generation AR technology. It addresses two main research questions: 1.) Which limitations and benefits of AR, reported in the current construction research body of knowledge, have consensus among various researchers exploring different use cases? and 2.) For the benefits and limitations reported that indicate divergence in findings, what contextual factors (i.e., factors related to the specific methods or motivations stated in the literature) are reported that may contribute to the differing reports? By analysing not only trends in limitations and benefits, but also contextual factors related to these, this work helps to elucidate the factors that may drive the observed trends in reporting. This is especially impactful when considering AR limitations reported that are seemingly contradictory. The results of this analysis will help researchers to strategically target studies that aim to mitigate the most consistently reported technological limitations and may also help to target implementation contexts that are conducive to effective AR use. The contribution of this work is in synthesizing findings based on disparate research papers in order to allow targeted future research and implementation efforts based on the evidence reported in the literature.

2. BACKGROUND

2.1 Augmented Reality

Augmented Reality (AR) is a technology that allows virtual content to be overlaid onto a user's view of their physical environment (Azuma, 1997). AR is considered to be a technology that falls in a broader spectrum of Mixed Reality (MR) that ranges from purely virtual experiences (i.e., VR) to purely real experiences (Milgram and Kishino, 1994). This spectrum of AR continues to be a lens through which various MR technologies are explored (Skarbez et al., 2021). Researchers have shown that AR has many useful applications in the construction fields, including: construction inspections and monitoring applications (Zollmann et al., 2014; Zhou et al., 2017); construction layout tasks (Chalhoub and Ayer, 2018, 2019a); and construction activity visualization (Wang et al., 2013). Studies such as these frequently report both benefits and drawbacks of AR. This section reviews the current literature and recent analyses of AR literature in order to illustrate the current state of knowledge and also the need for a better understanding in trends of reported benefits and drawbacks to current generation AR technologies.



2.2 Relevant Literature

Literature reviews provide a summary of research work that has been conducted in a given domain during a certain time frame. This form of research helps to analyse and describe collective results of relevant research studies in a useful manner. Literature reviews of the construction literature are common, since they can help to synthesize findings that may have been reported by various types of researchers who may be involved in this multidisciplinary field.

In recognition of the need to understand the trends in reporting among new visualization media in construction, several literature reviews have already been conducted. For example, a critical review exploring trends in virtual reality (VR) and AR for construction safety identified possible improvements to these technologies to enhance construction safety practices by examining journal publications from 2000 to 2017 (Li *et al.*, 2018). Rankohi and Waugh (2013) provided a statistical review of AEC-related AR literature published before 2012. This study classified the selected articles in their review based on improvement focus, industry sector, target audience, project phase, stage of technology maturity, application area, comparison role, and technology (Rankohi and Waugh, 2013). Chi (2013) summarized the results of 101 research efforts and outlined the research trends and opportunities for applying AR in the fields of AEC/FM. Cheng, et al. (2020) reviewed 87 papers exploring the applications of Mixed Reality (MR) and grouped them into four categories based on the stage of a project. These categories included applications in: architecture and engineering, construction, operation, and multiple stages. While these studies highlight the trends in benefits and drawbacks reported, they do not strategically explore the context of these claims, which highlights the opportunity to better understand factors that may influence whether AR will provide benefits or drawbacks.

Outside of the construction realm, researchers have conducted some literature reviews that explore both benefits and drawbacks of AR. For example, Akçayır and Akçayır (2017) reviewed 68 research articles related to AR in education, and found that AR promotes enhanced learning achievement, but can also lead to usability issues and frequent technical problems. Another study presented a review of the literature on AR applications that support science, technology, engineering and mathematics (STEM) learning by synthesizing 28 publications from 2010 to 2017. The findings of this review highlighted the importance of focusing the AR applications on science skill-based outcomes and offering metacognitive and experimental support (Ibáñez and Delgado-Kloos, 2018). In the medical field, Barsom, Graafland, and Schijven reviewed 27 publications that explore the effectiveness of AR applications in medical training, and found that in order to be of value, the AR applications must be able to transfer information to the user (Barsom *et al.*, 2016). These studies show that literature reviews can potentially guide future researchers by highlighting, aggregating and analysing important findings. While these systematic literature reviews contextualize both positive and negative trends in AR literature and illustrate the value to this type of analysis, similar studies do not currently exist in the construction domain.

The focus of this paper is on understanding the context of the benefits and drawbacks reported by AR researchers in the construction domain. This understanding of contextual factors is especially critical for instances when there is divergence in the reports among literature, where different researchers suggest the same technology may be beneficial or detrimental for seemingly similar construction applications. Moreover, an important aspect of this literature review is that it targets recent publications that have the opportunity to use current generation AR devices, which helps to eliminate the identification of trends in reports that may no longer be relevant because of technological advances.

3. METHODOLOGY

The authors of this work employed a structured methodology to identify and analyse papers related to AR in construction, as depicted in **Error! Reference source not found.** The following sections present the adopted method for defining the inclusion criteria necessary to identify peer-reviewed research articles and the process used for analysing these articles to identify trends in the literature where there is consensus and divergence in reports.

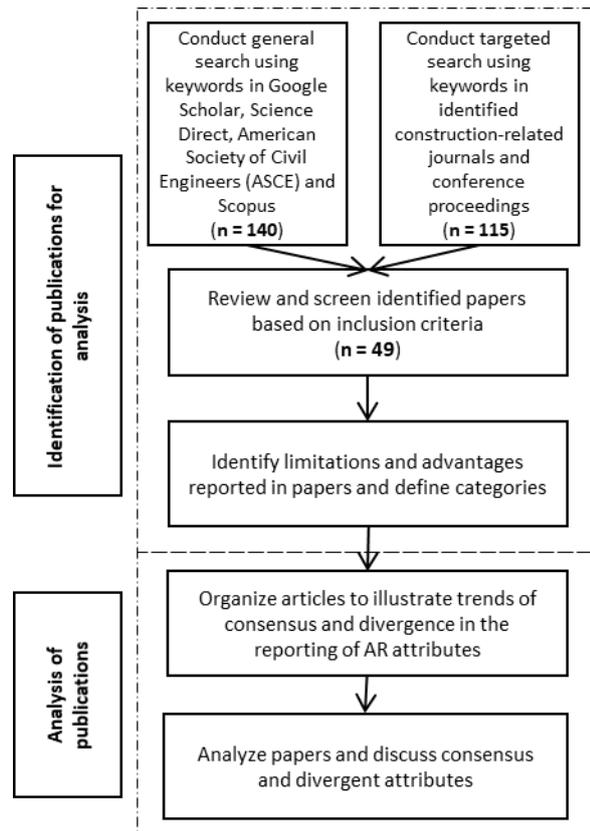


Figure 1: Flow chart detailing steps conducted in identifying and analyzing publications

3.1 Identifying publications for analysis

There are several different methods that prior researchers have employed to select manuscripts to include in literature reviews. For this analysis, the authors selected scientific articles including peer-reviewed conference and journal papers related to AR in the construction domain.

Two approaches for identifying relevant papers were used in this study. The first approach involved a targeted review of academic journals and conference proceedings known to include relevant literature. For this purpose, Scopus was used with the following search terms: “Augmented Reality” and “Mixed Reality”. Since the terms “Augmented Reality” and “Mixed Reality” are used interchangeably by different authors in different papers, both cases were included in the search to extract papers that fit the study scope. For this first approach, the journals selected related to the construction domain included: Automation in Construction, Journal of Information Technology in Construction, Journal of Computing in Civil Engineering, Journal of Construction Engineering and Management, Journal of Professional Issues in Engineering Education and Practice, Advances in Civil Engineering, Construction Innovation, Canadian Society for Civil Engineering, International Symposium on Automation and Robotics in Construction, and Computing in Civil and Building Engineering.

The second approach was a more general search involving a keyword search of Google Scholar, Science Direct, American Society of Civil Engineers (ASCE) and Scopus. As with the first approach, this latter approach included the following search terms: “Augmented Reality” and “Mixed Reality”. The purpose of this second approach was to ensure that construction-related AR studies that were not covered by the previously identified journals and proceedings were included, thus ensuring a broader survey of the literature.

Conference papers were included in the study to better reflect the current state of AR technology. While conference papers often represent smaller, more incremental, findings compared to journals, they also tend to be published faster. Therefore, by including conference papers in the search, it allowed the researchers to include more up-to-date reports by AR researchers.

In both approaches, the search was limited to a 7-year time period from 2013 to 2020. This period was chosen specifically to include publications that may have used head-mounted display (HMD) technologies and other AR-capable technologies that have recently entered the market and have received an overwhelming response from users and researchers (i.e. Microsoft HoloLens, DAQRI Smart Helmet). It is possible that this timeframe would also include publications that used older technologies that may not represent this latest generation of devices, but by limiting the search to only the last seven years, the frequency of use of older devices was anticipated to be reduced. Despite this intent, the authors included all studies that reported relevant works within this timeframe, regardless of whether they used HMD, marker-based, or other modes of AR.

In addition to limiting the search based on the year of publication, results were also filtered in Scopus to include those in the subject area of “engineering” with the document type “article” or “conference paper”, and the language in “English”. This process helped to reduce the hundreds of articles initially identified to only those that were likely to pertain to AR in the construction domain.

After articles were identified using the defined keywords, they were reviewed and evaluated to determine whether they were appropriate for the scope of the study. The criteria chosen for inclusion were the following:

- The papers must refer to actual uses of AR. Papers that only included mentions of AR (for example, as an opportunity for future work) were excluded from the results.
- The papers must be original works. Therefore, review papers were excluded.
- The papers must involve using AR for construction-related purposes. The authors included construction-related studies that were conducted in both onsite and controlled laboratory environments. By exploring both onsite and laboratory-based studies, the authors were able to define a broader sample of papers to better illustrate points of consensus or divergence among the construction research community.
- Papers that use the term AR, but refer to VR or other non-AR topics were excluded. The authors use definitions by Milgram and Kishino (1994) and Azuma (1997) for defining AR, as these are the most predominantly cited papers for defining AR (Khalek *et al.*, 2018). Both definitions require AR to involve some element of “reality” to be involved in a visualization experience. If papers do not describe any inclusion of reality in the visualization experience, the work was deemed to be related to VR and was excluded.

3.2 Analysis of identified publications

For all articles identified, all limitations and advantages reported for AR were extracted. This process was performed by examining the abstracts, discussion, and conclusions sections. In many of these papers, the original authors explicitly identified advantages of the technology for their specific applications. Similarly, academic publications frequently have subsections of their work that explicitly identify limitations of their use or development of AR. These direct statements of advantages and limitations enabled the authors on this paper to extract meaning from the published works without reinterpretation of findings.

Once all relevant reports about AR technology were identified (subsequently referred to as “attributes”), they were categorized in to groups of similar statements. Specifically, categories were defined when similar attributes were reported in more than one paper. In some instances, attributes were reported in specific papers, but were never echoed by other works. For example, a report was made about the calibration efficiency of AR for displacements at great distances (Zhou *et al.*, 2017), but this was not reported by other literature. While the authors of this work do not suggest that there are any flaws with the prior work, the fact that there are no other reports to confirm or question this finding hinders the authors’ ability to draw conclusions about trends in reports related to this particular attribute of AR. Consequently, in instances where an attribute was referenced by only a single paper, the authors of this work excluded it from their analysis. Once all attributes were defined and those that were reported more than once were categorized, the results were organized to illustrate trends for which there was consensus and divergence in research reporting.

For attributes where there was divergence in reporting, the authors re-examined the specific papers that were referenced in order to identify the underlying contextual factors that differentiated how AR was used. This process often involved identifying what exact construction use-cases were explored in the various papers and how the

descriptions of these use-cases may have differed. In order to provide practical meaning to the differences observed in the studies, the authors documented the contextual factors that they identified in the discussion section. This may help future researchers to strategically target (or avoid) certain implementation contexts in order to realize the greatest value from AR in new construction-related use-cases.

4. RESULTS AND DISCUSSION

The review of the literature initially identified a total of 255 papers. These papers were then screened based on the inclusion criteria presented previously, resulting in a total of 49 papers, which included 33 journal articles and 16 conference publications. The journal publications identified are shown in Table 1 with their corresponding number of publications. The conferences with papers from proceedings that were most frequently identified are shown in Table 2 with their corresponding number of publications.

TABLE. 1: Journal publications retrieved.

Journal	Original number of papers	Number of papers after screening	References
Automation in Construction	43	20	(Chen and Huang, 2013; Park <i>et al.</i> , 2013; Hou and Wang, 2013; Irizarry <i>et al.</i> , 2013; Kim, 2013; Kim <i>et al.</i> , 2013; Kwon <i>et al.</i> , 2014; Meža <i>et al.</i> , 2014; Omar and Nehdi, 2016; Zhou <i>et al.</i> , 2017; Kim <i>et al.</i> , 2017; Hou <i>et al.</i> , 2017; Chalhoub and Ayer, 2018; Liu and Seipel, 2018; Chu <i>et al.</i> , 2018; Fazel and Izadi, 2018; Kwiatek <i>et al.</i> , 2019; J. R. Lin <i>et al.</i> , 2019; El Ammari and Hammad, 2019; Chen <i>et al.</i> , 2020)
Journal of Information Technology in Construction	9	3	(Bademosi <i>et al.</i> , 2019; Chen <i>et al.</i> , 2019; Mutis and Ambekar, 2020)
Journal of Computing in Civil Engineering	13	4	(Hou <i>et al.</i> , 2013, 2015; Lin <i>et al.</i> , 2015; Chen <i>et al.</i> , 2016)
Journal of Construction Engineering and Management	5	1	(Wu <i>et al.</i> , 2019)
Visualization in Engineering	9	1	(Wang and Dunston, 2013)
Advanced Engineering Informatics	9	1	(Turkan <i>et al.</i> , 2017)
Advances in Engineering Software	6	1	(Meža <i>et al.</i> , 2015)
Journal of Professional Issues in Engineering Education and Practice	2	1	(Shirazi <i>et al.</i> , 2014)
Advances in Civil Engineering	3	1	(Wang <i>et al.</i> , 2018)
Personal and Ubiquitous Computing	22	1	(Schall <i>et al.</i> , 2013)
Construction Innovation	3	2	(Wang <i>et al.</i> , 2014; Zaher <i>et al.</i> , 2018)

TABLE. 2: Conference papers retrieved.

Conference Title	Original number of papers	Number of papers after screening	References
Canadian Society for Civil Engineering	3	1	(Chalhoub and Ayer, 2017)
Winter Simulation Conference	5	1	(Shirazi and Behzadan, 2013)
International Symposium on Automation and Robotics in Construction	29	8	(Chen and Chang, 2014; Kodeboyina and Varghese, 2016; Kim and Irizarry, 2017; Suk <i>et al.</i> , 2017; Hsu and Hsieh, 2019; Kyjaneek <i>et al.</i> , 2019; Xiang <i>et al.</i> , 2019; Z. Y. Lin <i>et al.</i> , 2019)
Computing in Civil and Building Engineering	5	1	(Gheisari <i>et al.</i> , 2014)
IOP Conference Series: Materials Science and Engineering	8	1	(Diaconu <i>et al.</i> , 2016)
Proceedings of the IEEE	81	1	(Zollmann <i>et al.</i> , 2014)



4.1 Consensus on Advantageous Attributes of AR

After reviewing these publications, the main beneficial and limiting attributes reported for AR were identified. These are presented in Figure 2. This Figure indicates that there are certain attributes for which there is consensus of reports regarding whether attributes of AR are advantages or disadvantages to the construction-related tasks studied. These attributes include learning/training time, immersiveness, field of view, occlusion, ease of implementation, and hardware and software performance. The following sections discuss the AR attributes which are considered to be advantageous, including learning/training time and immersiveness. These findings align with reports from other AR based literature reviews (Li *et al.*, 2018).

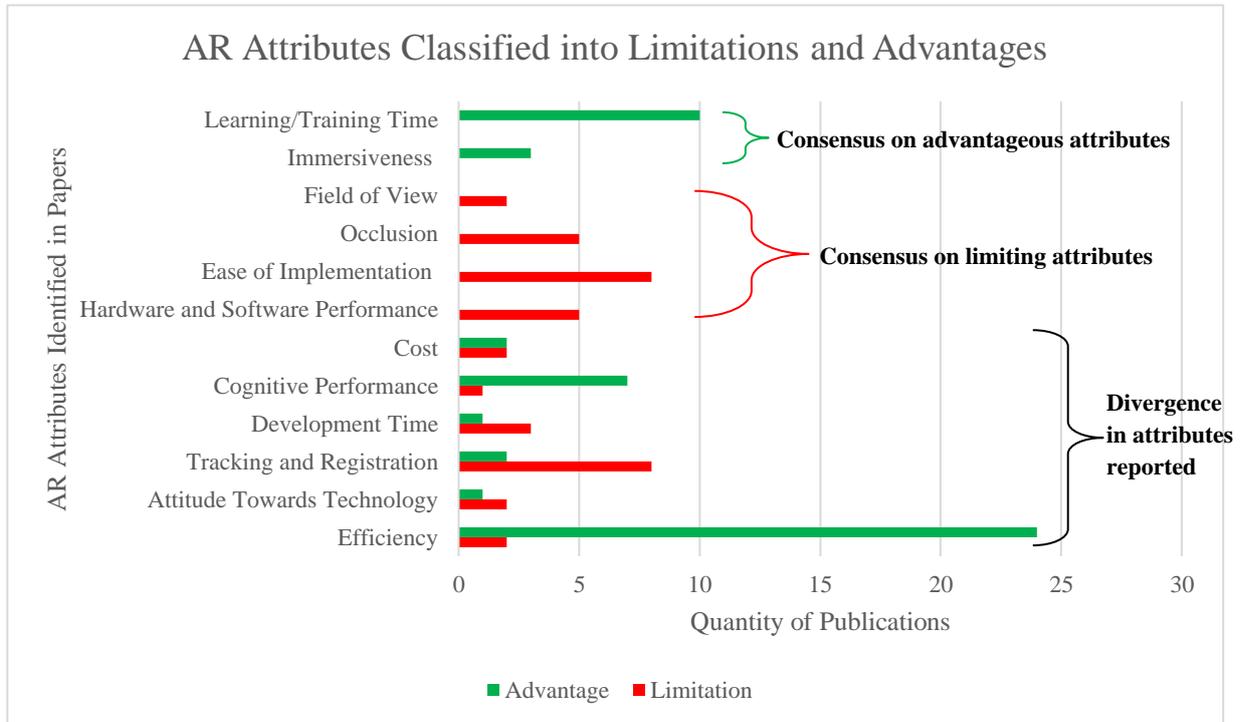


Figure 2: Attributes identified and classified into limitations and advantages

4.1.1 Learning/Training Time

The literature analysed consistently indicates that time to learn (or to be trained for) a construction-related application is reduced, or otherwise enhanced when using AR. An AR-based inspection method during tunnelling construction was reported to be practical in terms of training time since it allowed engineers to easily incorporate the new technology after a short training session (Zhou *et al.*, 2017). In the context of construction of liquified natural gas projects, workforce education and upskilling through an AR training system enabled the reduction of the learning time to improve the learning performance and the quality of training (Hou *et al.*, 2017). In a construction assembly process utilizing an animated AR system, the results revealed that the learning curve of novice assemblers was reduced (Hou *et al.*, 2013). Generally, users of AR technologies find it easy to learn and get used to the AR interface. This trend is also echoed in other non-construction fields, such as manufacturing (Tatić and Tešić, 2017). The reduced training time afforded through the use of AR subsequently leads to reduced employee training costs, which may help to justify the upfront costs that would be necessary to leverage AR training.

The papers reviewed were also explored to identify the attributes that may enable faster or enhanced training times. These benefits may be due in large part to the nature of construction tasks. While traditional construction drawings and computer-based design tools present design information in formats detached from the actual construction site, AR presents virtual content in context of the physical space. Traditionally, the plans and models are displayed in a CAD environment or other empty space, without any site-specific context. As a result, viewers must interpret modelled or printed content into a mental model that they must then contextualize to a physical construction site. Prior research suggests that this process of reinterpretation can be slow and prone to errors (Dadi *et al.* 2014).

Therefore, it is likely that the benefits reported related to AR reducing the time needed for construction training is largely due to reducing or eliminating the need for users to interpret drawings and BIM content into mental models that must be re-contextualized to the physical site.

4.1.2 Immersiveness

Immersiveness is another attribute, which was consistently reported as being an advantage of AR. Immersiveness can be understood as the ability of a device to seamlessly blend the 3D augmented visuals with the perceived real-world environment (Yuen *et al.*, 2011). In one study it was reported that an immersive view helped alleviate the mental workload experienced by participants who were using AR devices to monitor the “as built” progress against “as planned” progress on site (Liu and Seipel, 2018). Within a classroom environment, an immersive experience offering interactive 3D visualization features contributed to the students’ understanding of structural analysis (Turkan *et al.*, 2017). These reports indicate that the level of immersion afforded through AR may be one of the fundamental benefits that can be enabled through its use.

Generally, the construction field requires individuals to have the ability to visualize different construction tasks. However, for construction students and trainees new to the field, it may be relatively hard to visualize these tasks when certain aspects are not properly presented due to the inability to replicate actual project experiences in academic environments (Hartless *et al.*, 2018). It is likely that this consensus in reporting value to AR immersiveness is related to the fact that the view is specifically tailored to the user’s position and viewpoint. In this way, the resulting experience closely mimics what the viewer would see if virtual content physically existed. When virtual objects are seamlessly blended with the real environment, an individual would be enabled to assess the objects within their intended context, whereas less immersive experiences task users with conceptualizing not only the designed objects, but also their relevant contexts. Therefore, the reports suggest that there is consensus about the beneficial aspect of AR offering immersiveness that tailors a visual experience to the exact viewpoint of a user to contextualize the user’s view of the virtual content in the physical space.

4.2 Consensus on Limiting Attributes of AR

There are several beneficial attributes of AR that are consistently reported among construction researchers, but there are also several attributes that limit the effectiveness of AR in construction research. These reports highlight opportunities for future researchers to target problems that have consensus among the research community. The following sections review the attributes for which there is consensus in the body of literature about limiting attributes of AR.

4.2.1 Field of View

The field of view of different AR devices is considered to be a limitation by current AR researchers (Hedley, 2018; Liu and Seipel, 2018; Palmarini *et al.*, 2018). Current AR devices present a very limited field of view, which means the viewable area a user can see through the device does may not always allow them to see the entire model. This can potentially lead to misunderstandings by the user.

This limitation related to field of view appears to be well understood by current technology developers. As evidence of this, emerging AR devices, such as the Magic Leap One and the Microsoft HoloLens 2, are highlighting performance features related to increasing field of view. With a larger digital field of view, these new devices are marketed as being able to make holographic objects feel much more immersive than before (Heaney, 2019). While these claims will require validation by independent research, if they are partly or fully validated, the next generation of AR devices may provide a near-term solution to address the limitations reported by construction researchers.

4.2.2 Occlusion

Occlusion occurs when multiple objects overlap in a user’s field of view and objects in the background are partly covered by the overlapping objects in the foreground. When virtual content is hidden behind real objects without the AR device properly recognizing it, the virtual content that should be in the background is shown as if it is in front of the real object. This can be problematic since users could miss out on important aspects of the model if they do not recognize the intended arrangement of real and virtual objects. This issue is currently considered one of the most frequently cited issues in marker based augmented reality technology (Seo *et al.*, 2011), and various

methods to handle it have been proposed in the literature recently (Tian *et al.*, 2015). Handling occlusion is essential to provide a seamless integration of virtual and real objects in AR applications (Gimeno *et al.*, 2018).

Occlusion has been reported as a limitation of AR in construction by many different researchers (Meža *et al.*, 2014, 2015; Behzadan *et al.*, 2015; Kim *et al.*, 2017; Hedley, 2018; El Ammari and Hammad, 2019). On a construction site where safety hazard information is to be displayed in the form of augmented information, occlusion is considered problematic since missing out on safety information could lead to injuries and even fatalities (Kim *et al.*, 2017). When AR was used to improve the understanding and use of project information directly on site, the most disturbing factor, according to the participants, was the visual occlusion (Meža *et al.*, 2015). Similarly, when project documentation and design information were presented through AR technology, visual occlusion was reported to be a main problem that computer scientists and AR engine developers should solve (Meža *et al.*, 2014).

In the construction field, where construction tasks occur in an active and changing site, it is possible that the consensus among researchers in reporting occlusion as a major limitation is due to the challenging nature of the construction site. The occlusion phenomenon can lead to misinterpretation of on-site information, which could result in bad decisions. When observing the reported literature and examining the use-cases where AR brought significant value to the user, it is interesting to notice that no limitations from occlusion were mentioned in their reports (Hou *et al.*, 2013; Schall *et al.*, 2013; Zollmann *et al.*, 2014; Chalhoub and Ayer, 2017; Wang *et al.*, 2018; Pereira *et al.*, 2019). This might indicate that another remedy to this issue is to strategically choose use-cases where occlusion is either not an issue or not possible, such as in cases where users are not required to look far distances away where physical objects could more easily occlude the AR view.

4.2.3 Ease of Implementation

An important aspect of any technology is its ease of implementation. Several papers specifically reported on how much time and effort is required to apply AR in a certain environment. Many researchers agree that implementing AR in a construction setting is one of the technology's limitations (Schall *et al.*, 2013; Hou *et al.*, 2015; Kodeboyina and Varghese, 2016; Piroozfar *et al.*, 2018), particularly when markers are to be used on site (Kwon *et al.*, 2014; Zhou *et al.*, 2017; Fazel and Izadi, 2018). Researchers reported that the use of markers on site was not practical nor efficient because construction sites, specifically tunnelling sites, are not predictable in terms of their layout (Zhou *et al.*, 2017). Other papers reported that setting up a large number of markers on the job site was very time consuming, thus making the implementation of AR harder (Kwon *et al.*, 2014). Similarly, a marker-less way of finding coordinates of objects was recommended to make AR more flexible on the construction site, enabling an easier implementation (Fazel and Izadi, 2018). Moreover, when the benefits and limitations of AR for use in the AEC industry were investigated through surveys, it was reported that one of the biggest factors affecting implementation is the time needed to implement the technology (Piroozfar *et al.*, 2018). These findings consistently indicate agreement among the research community that improving the ease of implementing AR would provide benefits to the field.

4.2.4 Hardware and Software Performance

AR hardware and software are consistently reported to be limitations of the technology. Researchers have reported several problems relating to AR hardware and software including power limitations (Behzadan *et al.*, 2015; Kyjanek *et al.*, 2019), limited hardware capacity and the inability to scale well to large models (Meža *et al.*, 2014). Interestingly, this trend in reporting has been seen since AR's earliest stages (Caudell and Mizell, 1992; Feiner *et al.*, 1997) and is not specific to the latest AR devices. Although AR hardware and software are continuously improving, it seems logical that researchers attempting to implement cutting-edge use-cases will always identify the technology's weaknesses because they are frequently aiming to perform tasks that have never been done before. Therefore, even though newer devices will have better performance, it is likely that this finding simply indicates that researchers will continue to desire even better performance. Therefore, it is possible that, even though future AR development will address the currently cited problems, it may not completely eliminate reports of a lack of hardware or software performance in future publications.

4.3 Trends Indicating Divergence

While the findings of beneficial aspects of AR largely align with prior AR review and literature review papers, the authors of this work go on to also explore the attributes of AR that do not result in agreement among all researchers. These attributes include cost, cognitive performance, development time, tracking and registration, attitude towards

the technology, and efficiency of AR in construction environments. The following sections discuss the specific attributes reported where there is consensus and divergence in reporting about the benefits and drawbacks of AR in the construction domain.

4.3.1 Cost

The actual cost of implementing AR is frequently addressed in many different publications, but it often leads to different viewpoints about whether it is comparatively expensive or inexpensive. While many studies mention the high cost of AR as a limitation (Hou *et al.*, 2015; Agarwal, 2016; Kodeboyina and Varghese, 2016; Omar and Nehdi, 2016; Kim *et al.*, 2017; Piroozfar *et al.*, 2018), other studies find the cost of implementing AR in the construction field as an advantage (Adăscăliței and Bălțoi, 2018; Chu *et al.*, 2018; Fazel and Izadi, 2018). The diverging opinion on cost of AR is largely intuitive when considering the very broad range of available AR devices, with varying prices in the market. For example, there are \$20 cardboard systems that enable smartphones to deliver AR experiences, and also more sophisticated AR systems that cost thousands of dollars. To further illustrate the range of prices for AR hardware, a list of several AR devices and their approximate current prices is provided in Table 3. In addition to the varying costs of the hardware, AR implementation may also require specific software packages to support development efforts. There can be advantages and disadvantages to using expensive and inexpensive options during development. Leveraging inexpensive hardware and software options can encourage widespread application of AR, but this can also provide challenges in developing a seamless AR experience (Kodeboyina and Varghese, 2016).

TABLE 3: AR devices and prices in the market.

Device	Approximate Price (in US Dollars)
Daqri AR Smart Helmet	~\$15,000
Microsoft HoloLens 2	~\$3500
Microsoft HoloLens	~\$3000
Epson Moverio BT-300FPV Drone Edition	~\$700
Google Glass	~\$1500
Vuzix Blade AR	~\$1000
Meta 2	~\$1500
Kopin SOLOS	~\$500
Garmin Varia Vision	~\$400
Google Cardboard	~\$20

The variations in claims about AR being expensive or inexpensive is likely related to one of several contextual factors that differed between studies. First, it is worth noting that some of the papers explored in this work used inexpensive mobile tablet computers and reported that low cost was a benefit of AR (Chu *et al.*, 2018). Conversely, other studies used more expensive AR hardware to display large models and similarly claimed that the cost of AR can be considered a limitation (Hou *et al.*, 2015). While there is some divergence in reports based on the upfront cost of AR, it should be recognized that the actual use-case explored has a substantial impact on whether or not researchers and practitioners can expect to see a return on investment from AR. In other words, for applications where highly sophisticated AR systems are required and may not directly lead to substantial time savings or reduction in errors, researchers are likely to report concerns with costs regardless of the exact upfront cost associated with their chosen device. Conversely, when examining literature that uses AR for construction assembly tasks or other time-consuming tasks, time savings and reductions of errors may make even the most expensive consumer electronic devices seem reasonable because of the savings they afford. Therefore, it is most accurate to conclude that while the cost of AR implementation leads to divergent reports in the literature, it is probably best that future researchers do not aim to generalize the cost of AR as either expensive or inexpensive, because this claim is highly subject to a specific application context. Instead, it is probably a wiser strategy to explore cost for a specifically targeted use-case, considering that while implementation will require upfront investment for the hardware and software, its payback will be highly dependent on the specific use-case that will be explored.

4.3.2 Cognitive Performance

There are divergent reports about the impacts of AR on cognitive load reported by users. Some studies suggest that implementation of AR into the construction industry leads to reduced cognitive load among users, allowing for better performance (Hou *et al.*, 2013, 2015; Meža *et al.*, 2014; Omar and Nehdi, 2016; Chu *et al.*, 2018; Liu and Seipel, 2018; Chalhoub and Ayer, 2019b). Conversely, other research found that AR might actually result in an increased cognitive load (Kim *et al.*, 2017). Furthermore, one paper found that even if there is a decrease in

cognitive load, it may not improve cognitive performance (Wang *et al.*, 2018). The divergent reports on AR for cognitive load may relate to the specifics of how AR is implemented.

This difference in reports between papers on the impact of AR on cognitive performance seems to be dependent on the type of task performed by the user. For example, in the context of a natural gas project where AR was used to facilitate onsite progress monitoring, results showed that AR helped alleviate the mental workload undergone by the users (Liu and Seipel, 2018). In this example, AR enabled users to see visual information regarding progress. This process-based information is not naturally visible without a technological interface, which may have enabled it to make it comparatively easier to understand. Conversely, in the context of a construction hazard avoidance system using wearable AR, researchers reported that the device can distract workers from concentrating on tasks (Kim *et al.*, 2017). When considering the identification of hazards on a job site, these should theoretically be visible to workers who have had proper safety training (i.e. recognizing a moving vehicle in order to avoid its path of travel, or noticing the absence of fall protection at the edge of a floor in order to recognize the need to install it). Augmenting visual information to a user about a topic that they should already be able to see may contribute to the reported cognitive overload and distraction. This finding is generally echoed by researchers in non-construction domains who explored AR driver assistance systems that were intended to highlight hazards, but led to distraction (Halit *et al.*, 2014). More generally, these reports seem to indicate that when AR is used to overlay information that cannot naturally be seen, it may support a reduction in cognitive load. However, when AR is used to highlight visual information that is already visible to users, it may lead to cognitive overload.

4.3.3 Development time

The research papers analysed frequently reported divergent findings about the time required to develop AR applications. In some instances, construction researchers reported that the development time is a limitation of AR because of the coding requirements and challenges associated with displaying large models (Meža *et al.*, 2014). Conversely, other researchers stated that developing AR applications is not a major issue, and that stakeholders could develop AR applications and various simulations without substantial time and resources (Adăscăliței and Bălțoi, 2018). While the time difference of the studies can account for the challenges experienced in the development of content, with older studies reporting challenges in this respect as a consequence of the relatively less mature stage of the technology, more recent studies have also reported development time as being a limitation (Xiang *et al.*, 2019).

Instead, this divergence in reports regarding AR development time is logical when considering the wide range of applications that could be developed and the varied levels of investment needed, depending on the specific application. The amount of time and resources required to develop a functional application is directly related to the specific performance attributes required of the application. Generally, developing AR applications incorporating very large models or elaborate user interfaces require high processing power and long development time when compared to smaller models with simpler user interfaces.

Therefore, the findings from these divergent reports suggest that future AR developers should carefully consider the needs of their application and aim to produce the simplest possible AR application that still meets the needs of the targeted user. While this finding may seem intuitive, the frequency of reports indicating development time as a limitation seems to highlight that this can still be problematic. This may be an opportunity for future AR researchers and practitioners to leverage development strategies from other fields such as Human-Centered Design (Abrás *et al.*, 2004). This type of development approach encourages rapid and iterative building of applications for testing. This may help to define minimally viable AR solutions that address the needs of the targeted construction user without compromising return on investment because of long development times.

4.3.4 Tracking and registration

Tracking and registration are among the most critical issues for AR applications (Rabbi, 2012). Registration refers to the proper alignment of virtual objects to the real-world environment, while tracking relates to the identification of objects, which can be done either through marker or marker-less methods. In the studied literature, there have been divergent reports related to tracking and registration efficiency of AR devices. Some researchers report current AR tracking and registration processes to suffer from limitations (Hou *et al.*, 2015; Kodeboyina and Varghese, 2016; Reiners *et al.*, 2016; Hedley, 2018; Chen *et al.*, 2020; Mutis and Ambekar, 2020) while other researchers view it as an advantageous feature (Schall *et al.*, 2013; Zollmann *et al.*, 2014). For example, in a prototyped construction piping scenario, where AR was used to facilitate piping assembly in a lab-based

environment, tracking and registration were reported as challenges in unprepared environments and were not ready to be applied in a real outdoor construction site (Hou *et al.*, 2015). This study clearly presented the tracking and registration of AR as a limitation. Conversely, when researchers explored a mobile AR application for on-site progress monitoring, tracking and registration were reported to be working robustly under different lighting and environmental conditions (Zollmann *et al.*, 2014). Another study, echoed this finding that tracking and registration was effective in various conditions when using a commercially available AR device (Hedley, 2018).

These findings seem to indicate that the performance, or lack of performance, related to tracking and registration is highly dependent on the device chosen for use and also the use-case in which it is intended to be used. For instances where users are likely to quickly modify their view of the space or look around for various information, AR may continue to exhibit registration and tracking issues. Similarly, if AR is intended to be used in unprepared environments, it can lead to inaccurate positioning and orientation (Schall *et al.*, 2013). While these findings may not automatically mean that AR should not be used, the findings should at least be considered by developers. If the success of the application is contingent on accurate tracking and the exact context of use is not known or controlled by the researchers and developers, it may be unwise to rely on an AR application for accurate tracking and registration.

4.3.5 Attitude towards technology

Several of the papers reviewed also reported on attitudes expressed by AR users about the technology. The reports in the sample of papers considered in this paper indicated an approximately even split in reports about user attitudes toward AR. Several papers clearly indicated that users in the construction domain do not have a positive attitude toward AR (Meža *et al.*, 2015; Liu and Seipel, 2018; Piroozfar *et al.*, 2018). For a field that has been criticized for historically low productivity compared to other domains and low adoption of innovative technologies (Fulford and Standing, 2014), these findings generally align with expectations. However, it was noteworthy that many papers reported users in the construction domain having a positive attitude toward AR (Wang and Dunston, 2013; Chen *et al.*, 2016; Chalhoub and Ayer, 2017).

The findings seem to indicate that making a blanket statement that AR is or is not viewed positively by construction users is insufficiently defined. When examining the differences between the papers reviewed, the authors of this work observed consistency in reports based on whether the technology offered benefits directly to the targeted user or not. For example, in instances when the AR application made a task easier to perform by the AR user, papers frequently reported positive attitudes toward the technology (Wang and Dunston, 2013; Chen *et al.*, 2016; Chalhoub and Ayer, 2017). Conversely, when the AR application was intended to offer benefit to the project on the whole, but not necessarily to the specific AR user, papers frequently reported negative attitudes toward AR (Meža *et al.*, 2015; Liu and Seipel, 2018; Piroozfar *et al.*, 2018). This trend in reports seems to indicate that future developers should actively consider how they implement AR in order to directly benefit targeted users. Even if an AR application is well designed to provide value to the project on the whole, the reports observed in this analysis suggest that it may be unlikely to meet accepting users if it does not directly offer benefit to them.

4.3.6 Efficiency and Performance of AR in Construction Environments

Construction environments often involve unpredictable and constantly changing spaces that may involve loud noises, varied lighting conditions, and changing equipment layouts. This can impact the efficiency and performance of AR. The publications analysed diverged in their reporting on AR's performance in this potentially challenging environment. In some cases, researchers stated that the performance of AR was limited because of environmental conditions (Behzadan, Dong and Kamat, 2015). Conversely other papers reported the performance of AR to be efficient and effective, even in a construction environment (Kim *et al.*, 2013; Albert *et al.*, 2014; Agarwal, 2016; Diaconu *et al.*, 2016; Omar and Nehdi, 2016; Hou *et al.*, 2017; Zaher *et al.*, 2018).

Although AR was reported to be efficient in several construction applications, it is important to note that several of these studies were conducted in controlled environments (Schall *et al.*, 2013; Agarwal, 2016; Omar and Nehdi, 2016; Chalhoub and Ayer, 2017, 2018; Chu *et al.*, 2018) or reflected preliminary results that do not meet all of the real-world conditions. When tested in realistic site conditions, important AR features such as image registration and speech recognition can be affected (Behzadan, Dong and Kamat, 2015). It is critical for AR applications that use voice commands to be properly adjusted for noisy environments, or potentially rely on other non-audible methods of interaction to avoid this problem. It is also important to consider how other AR features (registration, tracking, occlusion) can be affected when used in uncontrolled environments. It is possible that, as AR devices

evolve, they may become better at handling these challenges. However, given the unpredictable nature of construction environments and the reports indicating problems when AR was implemented on active sites, the reports would suggest that it would be wise for researchers to carefully design user interfaces that can function effectively even in challenging site environments, or to target use-cases that support construction offsite in more controlled environments.

4.4 Limitations

This work provides insights into the trends in reports about AR in construction, but the authors recognize that it does have some limitations. One limitation of this work is related to the small sample of papers dealing with AR in construction tasks in a 7-year period. This is likely to be inevitable when exploring new, current-generation technologies. The authors recognize that other researchers may possess different viewpoints that are potentially confirmatory or contradictory to those identified in this study, but if these perspectives were not published at the time of this analysis or were not detected using the search criteria defined, they may have been omitted from this work. It is also possible that factors related to AR performance other than just advantages and limitations have been reported in other domains that explore its use. Even if these reports from other fields may help to validate or question the findings of this construction-focused study, they were excluded due to the scope of papers defined. While this potentially limits the extent to which the findings in this work are comprehensive, any opinions or findings that were not published or found in construction technology-related publications are equally likely to be missed by future AR researchers. As a result, while the trends observed in this work may not necessarily be comprehensive of all possible viewpoints, they still do effectively illustrate the general trends in published literature, which can help to guide future studies based on evidence from recent works.

Additionally, the findings related to contextual factors that may have impacted AR performance are predominantly qualitative. Comparing different studies that explored different use cases or technologies can make direct comparison of findings and claims difficult to quantify. For example, while the authors aimed to identify contextual factors within the manuscripts identified that were likely to have contributed to the reports on those papers, it is possible that a completely different element in the works studied that may not have been stated in the publications led to reported advantages or limitations. While this limits the extent to which the authors can specifically quantify how much certain contextual attributes would impact the success of AR, observing the trends where there is consensus and divergence in reporting can still help researchers to quickly identify the attributes of their targeted AR application where more use case-specific planning would need to occur to mitigate some of the potentially detrimental aspects of the technology.

5. CONCLUSION

This study explores the trends in performance attributes reported in the past 7 years by construction researchers exploring current generation AR devices. The trends seen in the literature were classified into 10 categories. For some performance attributes, including learning/training time and immersiveness, the findings of this work consistently indicate that there is consensus that AR offers beneficial performance attributes for construction applications. For other performance attributes, including occlusion, ease of implementation, hardware and software performance, the findings consistently indicate that the performance of current generation AR devices may be limited for construction applications.

In addition to presenting trends where the AR research community has reached consensus, this paper also presents performance attributes of AR where there is divergence in reporting by researchers. The following performance attributes had divergent reports among construction-related AR literature: cost; cognitive performance; development time; tracking and registration; attitude towards the technology; and usability in construction environments. After reviewing the publications that reported divergent performance attributes of AR, the authors identified several contextual attributes related to how AR was implemented that may have impacted whether or not researchers report it to be beneficial or detrimental to construction performance. The identification of these contextual factors will enable future AR developers to strategically incorporate or avoid certain conditions during implementation to maximize their chance of realizing the beneficial aspects of AR that have been reported in the literature. Furthermore, the findings show that for many performance attributes of AR, a cursory review of literature may not adequately inform subsequent development efforts because different researchers may report divergent and, at times, contradictory findings. Therefore, the structured review process employed in this work

enables the research community to more effectively learn what performance attributes of AR have led to general consensus and divergence among recent AR researchers. The contribution of this paper is in identifying the specific contextual attributes related to AR in construction that consistently enable or hinder its performance. These findings will allow researchers and industry practitioners to strategically decide on the applicability of AR, enabling them to avoid critical pitfalls by recognizing contextual attributes that affect performance. Furthermore, as new AR devices emerge into the market, this study may guide the industry in planning for how to use the new technologies.

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