The Use of Augmented Reality for Communication in Uncontrolled Construction Environment

by

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ABSTRACT

The construction industry requires effective communication between project stakeholders in various locations. This communication can be facilitated by in-person site visits or phone calls. However, these traditional methods can lead to wasted travel time or the omission of critical visual site details. In theory, augmented reality (AR) can support consistent understandings of site environments in a similar way to in-person visits also with the efficiency of phone calls. Similar to the telestrator (i.e. video marker) seen during a football game, virtual content is overlayed over a real physical view of a space. While many studies explored the potential benefits of AR application for communication in controlled environments, they also mentioned the necessity to implement AR in uncontrolled environments. This dissertation's main objective is to explore AR in live construction sites. First, this research explores literature through a comprehensive review to understand what has been documented in the literature: what shows consensus, what shows divergence among the existing studies, and understand the different contexts that would trigger challenges. Second, this research evaluates the utilization of augmented reality (AR) by exploring practitioners performing AR calls on field in real-time highway construction. During these trials, an on-site user engaged in an AR call with an off-site user. These calls were analyzed, and follow-up interviews were then conducted with the users to get a rich understanding of the users' behaviors and perceptions. This field testing enabled the author to explore beneficial and challenging factors that affected the use of AR, categorize them, and identify ways in which AR technologies may, and may not, immediately support site-based communication for ongoing construction application. Third, this research establishes a decision-making framework that incorporates the

advantageous and challenging factors outlined in paper 2. This framework considers various contextual factors and user behaviors related to the application in order to address and mitigate some of the challenges. This framework is given to users to test its content, comprehensiveness, and workflow. The framework is then updated and developed based on three rounds of Delphi panels to get a final consensus from users. The results of this dissertation offer a tool for users who never used AR on site before, support its use when it is effective, and avoid it when it is not.

DEDICATION

To my husband, your love and unwavering support have been my constant motivation throughout this journey.

To my family, this dissertation is a tribute to your belief in me and a reflection of the values you've instilled in my heart.

Thank you for being my pillars of strength.

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I would like to extend my heartfelt appreciation to my co-chairs, Dr. Steven Ayer and Dr. Mounir El Asmar. Your guidance, expertise, and unwavering support have been indispensable throughout this journey. Your mentorship has shaped this dissertation and enriched my academic growth in profound ways. Thank you for your dedicated commitment to my success. I also want to express my gratitude to Dr. Kristen Parrish for her valuable contributions and additional feedback. Your insights have provided valuable perspectives that have significantly enhanced the quality of this work. Your involvement is greatly appreciated and has made a meaningful impact on the outcome of this study.

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CHAPTER 1

Introduction

1.1 Motivation

The construction sector provides a major contribution to the economy of every country and the growth of any nation. Governments show high interest in the construction industry considering the financing invested in it. Based on the Associated General Contractors of America (*1*), the construction industry has more than 753,000 employers with over 7.8 million employees and creates nearly $1.8 trillion worth of structures each year (*2, 3)*. Despite the impact of this industry, it has been criticized for poor production, often because of challenges with communication (*4, 5*). These production problems can take the form of time and cost overruns, legal disputes, and project failures. Due to its specific characteristics, the construction industry is a diversified and complex environment. It involves numerous stakeholders and clients like property builders, property developers, consultants, material suppliers, contractors, and sub-contractors. According to Gallaher et al., (2004), when this communication between all parties is unsuccessful and ineffective, 30% of the value of the project goes to waste (*6*). The efficiency and effectiveness of the construction process strongly depends on the quality of communication (*7*). These facts emphasize the need for effective communication in the industry to facilitate the flow of information supporting the decision-making backing project outputs (*8, 9*).

In the industry, communication is facilitated through traditional methods like site visits and the use of cellphones (*10*). Site visits offer an in-person discussion which promotes trust between stakeholders. It allows a natural flow of information, and physical exploration of site details and understanding of site problems (*11*). However, site visits require time to physically travel to and from remote sites, especially highway projects. While conducting site visits offers beneficial aspects, it leads to wasting time and money (*12*). Conversely, the use of cellphones allows for quick conversations and direct involvement of off-site personnel. However, verbal exchanges with limited vision of the site cause misinterpretation and misunderstanding of critical site details, which can result in bad decision-making. These facts emphasize the need for new and innovative communication methods that offer the benefits of site visits in addition to the benefits of verbal conversation.

Augmented reality (AR) is a technology that allows users to see the real world with virtual objects superimposed onto or composed with the real world (*13*,*14*). Thus AR can offer the benefits of sharing site context visualization with the efficacy of cellphones.

AR has been explored in the construction industry to support inspections (*15*,*16*), visualization (*17*,*18*), mapping (*19*,*20*), education (*21*,*22*), safety (*23*,*24*), and communication (*25*,*26*,*27*,*28*). However, most of these studies have explored the use of AR in controlled environments or required extensive training for users. While previous studies explored the use of AR as a new technology and its impact on the industry, many researchers consistently mentioned that their work might be limited if not tested in a real environment. Cote et al., (2014) in their study mentioned that investigating the development factors of the 3D perception in a construction context would be more valuable (*29*)**.** Chalhoub et al., (2018) stated that site conditions such as labor congestion, noise and safety concerns, could affect the performance of the user (*30*). Shin and

Dunston (2009) encourage the need for future studies to be conducted on construction sites (*31*). Similar, Wang (2009) and Wang and Dunston (2013) stated the necessity of studying AR in a real-world context (*32, 33*). The high percentage of the number of AR studies conducted in controlled environments helped in getting primary feedback about AR implementation. However, testing the application in real environment surrounding helps evaluate the flexibility of AR leading to real improvements in performance and productivity (*30*). Thus the need to conduct uncontrolled environment-based studies which this dissertation focuses on.

The content of this dissertation is composed of five chapters. This first chapter represents a summary of the motivation and the methods used in the following three chapters. Figure 1., shows the core of the dissertation: chapter 2, 3, and 4 and the link between them. In the last chapter a summary of the findings and contributions of each chapter is represented.

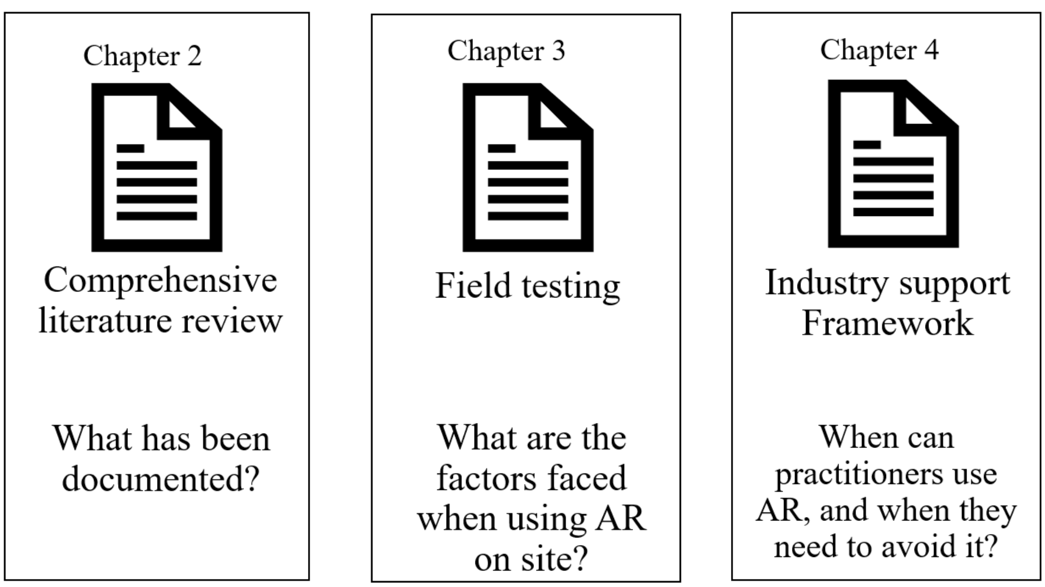


Figure 1: Representation of the Three Chapters and their Motivating Questions

1.2 Overview of the Chapters

1.2.1 Chapter 2

This chapter represents a comprehensive review of the literature. It answers two main questions:

1. What attributes related to AR for synchronized communication are consistently reported to be either challenging or beneficial by researchers?
2. For the attributes where researchers diverge in reports of benefits or drawbacks, what contextual elements within the reports differ in a manner that may contribute to the differing reports?

To answer these questions a systematic review of the literature was done. The author divided the method into three structural phases: criteria selection, search and filtering, data collection and classification. As a first step, the authors identified three key words highly related to the topic: "augmented reality, construction, and augmented reality". Then, journals and peer-reviewed conference proceedings were chosen that are related to the construction industry and regularly include publications relevant to innovative construction strategies like AR. After reviewing parts of the collected papers, the author was able to go from 171 papers to 59 papers. These papers were then studied more in depth and the author categorized the papers into four sections: type of projects, type of environments, the benefits mentioned, and the challenges. Consequently, the benefits and the challenges that show consensus among papers were retrieved as well as the attributes that show divergence among the same papers. At the end, a comparison among the contextual factors of the papers was conducted to try to understand the reason behind this divergence. This whole methodology is explained more in depth in the chapter in addition to the results, the findings, and their analysis. The findings of this study contribute to the literature by enabling researchers to include or exclude contextual factors to gain or mitigate reported benefits or challenges when using AR in construction for synchronized communication.

1.2.2 Chapter 3

This chapter is field testing, an exploratory study investigating the efficacy of AR calls in uncontrolled settings (i.e., active construction sites) by interviewing and recording practitioners who are using AR, in order to identify behaviors and perceptions that influence communication efficiency and effectiveness. The main objective is to identify factors that could potentially impact the success of using AR for communication on active construction sites. The factors identified are organized into categories related to technology, people, process, and environment.

Data collection is based on video recordings and follow-up interviews conducted with practitioners. The videos were analyzed based on a thematic analysis to understand what the users did on site (i.e. behaviors) and the interviews were analyzed to understand what the users think. The same users working on-site called the same users off-site (both working for the same company) to have a repetitive observation of the same variables. Based on, the author collected a rich understanding of the behavior of the users towards AR applications. This informed not only the factors that affected the implementation of AR but an understanding of the actions that the users acquired over time to overcome the observed challenges. Forty-six codes were extracted, revealing fourteen key factors classified into categories spanning technology, people, process, and environment. Some factors offered by this technology represent benefits; others pose challenges. AR communication tools make the communication process, sharing data, and recording of information more efficient and useful during construction and post-construction. The challenges related to AR application are associated with the type of tool used, its features, and the surroundings. Some of these factors were addressed by simple solutions suggested by the users and the authors, such as tinted films; others were overcome by the users' repetition and practice.

Future research could focus on training workshops that allow users to practice in uncontrolled real-life environments, similar to the work presented in this paper, and creating an instructional framework to help users choose the best device supporting AR application depending on particular scenarios and conditions they are facing which open the gate for the next chapter.

1.2.3 Chapter 4

This chapter built on the previous findings by creating a decision-making framework that may help industry practitioners use AR in a specific context with specific tools. The objectives of this chapter are: 1. To create a guiding framework for users who have not used AR yet. 2. Understand the ways in which this framework might guide decision making for someone who hasn't used AR. 3. Support people to use this technology where it is effective and to avoid it when it is not.

Using the benefits and the challenges revealed within specific contexts, the author created a decision-making framework for the tools that support AR implementation on site. This framework was then developed and tested using modified Delphi panels. The Delphi technique is intended to obtain the consensus of qualified and carefully selected experts on a particular subject or uncertain issue by exposing them to a set of updated questions combined with opinion-based feedback (*34*). Two preliminary rounds of Delphi were done using online surveys. Two types of users were selected: 1. Users with previous experience, 2. Users without previous experience. Each type of user received a different survey. The surveys were based on four realistic scenarios to test their ability to understand the framework and choose the right device based on specific contexts and needs. In addition, to questions related to the format of the framework, its workflow and its comprehensiveness. The third round of Delphi is based on a group discussion to obtain final feedback and consensus among the users. After the collection of data, a filtering process was done before updating the framework. The method, the filtering process, and the framework are presented more in depth in this dissertation's section.

References

1. The Associated General Contractors (AGC) of America (2018). Construction Data. The Construction Association of America.

2. Sui Pheng, L., Shing Hou, L., Pheng, L. S., & Hou, L. S. (2019). The economy and the construction industry. *Construction Quality and the Economy: A Study at the Firm Level*, 21-54.

3. Importance of Construction Industry in The Economy and The Use of Construction Equipment. Holloway. (2018). Importance Of Construction Industry In The Economy And Use Of Construction Equipments - Blog (hhilifting.com)

4. Gamil, Y., & Rahman, I. A. (2017). Identification of causes and effects of poor communication in construction industry: A theoretical review. *Emerging Science Journal*, *1*(4), 239-247.

5. Kazi, A. S. (Ed.). (2005). *Knowledge management in the construction industry: A socio-technical perspective*. Igi Global. p.384. DOI: 10.4018/978-1-59140-360-9

6. GCR, N. (2004). Cost analysis of inadequate interoperability in the US capital facilities industry. *National Institute of Standards and Technology* (NIST), 223-253.

7. Hoezen, M. E. L., Reymen, I. M. M. J., & Dewulf, G. P. M. R. (2006, July). The problem of communication in construction. In *CIB W96 Adaptable Conference, University of Twente)*.

8. Emmitt, S., and Gorse, C. (2006). Communication in Construction Teams. Taylor & Francis eLibrary.

9. Dainty A., Moore D. and Murray M. (2006). Communication in construction, theory and practice. Taylor&Francis, London. DOI:10.4324/9780203358641

10. Sperber, D., & Wilson, D. (1986). Relevance: communication and cognition Blackwell.

11. Cheng W. L. E., Li H., et al. (2001). Network communication in the construction industry. Corporate Communications: *An International Journal*; Vol.6, nb.2.61-70. ISSN1356-3289

12. Minooei, F., Sobin, N., Goodrum, P. M., & Molenaar, K. R. (2018). Managing Public Communication Strategies in Accelerated Highway Construction Projects. *Transportation Research Record*, *2672*(26), 1-10.

13. Milgram, P., & Kishino, F. (1994). A taxonomy of mixed reality visual displays. *IEICE TRANSACTIONS on Information and Systems*, *77*(12), 1321-1329.

14. Azuma, R. T. A. (1997). “Survey of Augmented Reality.” Presence: Teleoperators and 155 Virtual Environments.

15. Moreu, F., Lippitt, C., Maharjan, D., Aguero, M., & Yuan, X. (2019). Augmented reality enhancing the inspections of transportation infrastructure: Research, education, and industry implementation.

16. Salamak, M., & Januszka, M. (2015). BIM models and augmented reality for concrete bridge inspections. In *11th Central European Congress on Concrete Engineering CCC2015, Hainburg* (pp. 25-28).

17. Honkamaa, P., Siltanen, S., Jäppinen, J., Woodward, C., & Korkalo, O. (2007, April). Interactive outdoor mobile augmentation using markerless tracking and GPS. In *Proc. Virtual Reality International Conference (VRIC), Laval, France* (pp. 285-288).

18. Woodward, C., Hakkarainen, M., Korkalo, O., Kantonen, T., Aittala, M., Rainio, K., & Kähkönen, K. (2010, November). Mixed reality for mobile construction site visualization and communication. In *Proc. 10th International Conference on Construction Applications of Virtual Reality (CONVR2010)* (pp. 4-5).

19. Behzadan, A. H., & Kamat, V. R. (2008, December). Simulation and visualization of traffic operations in augmented reality for improved planning and design of road construction projects. In *2008 winter simulation conference* (pp. 2447-2454). IEEE.

20. Roberts, G. W., Evans, A., Dodson, A., Denby, B., Cooper, S., & Hollands, R. (2002, April). The use of augmented reality, GPS and INS for subsurface data visualization. In *FIG XXII international congress* (Vol. 4, pp. 1-12).

21. Soria, G., Ortega Alvarado, L. M., & Feito, F. R. (2018). Augmented and virtual reality for underground facilities management. *Journal of Computing and Information Science in Engineering*, *18*(4), 041008.

22. Cote, S., & Mercier, A. (2018, March). Augmentation of road surfaces with subsurface utility model projections. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)* (pp. 535-536). IEEE.

23. Kim, K., Kim, H., & Kim, H. (2017). Image-based construction hazard avoidance system using augmented reality in wearable device. *Automation in construction*, *83*, 390-403.

24. Park, C. S., & Kim, H. J. (2013). A framework for construction safety management and visualization system. *Automation in Construction*, *33*, 95-103.

25.Gurevich, P., Lanir, J., Cohen, B., & Stone, R. (2012, May). TeleAdvisor: a versatile augmented reality tool for remote assistance. In Proceedings of the SIGCHI conference on human factors in computing systems (pp. 619-622).

26. Lin, T. H., Liu, C. H., Tsai, M. H., & Kang, S. C. (2015). Using augmented reality in a multiscreen environment for construction discussion. *Journal of Computing in Civil Engineering*, *29*(6), 04014088.

27. Côté, S., Trudel, P., Desbiens, M., Giguère, M., & Snyder, R. (2013). Live mobile panoramic high accuracy augmented reality for engineering and construction. *Proceedings of the Construction Applications of Virtual Reality (CONVR), London, England*, 1-10.

28. Ganah, A., Anumba, C. J., & Bouchlaghem, N. M. (2001, July). Computer visualisation as a communication tool in the construction industry. In *Proceedings Fifth International Conference on Information Visualisation* (pp. 679-683). IEEE.

29. Côté, S., Beauvais, M., Girard-Vallée, A., & Snyder, R. (2014). A live augmented reality tool for facilitating interpretation of 2d construction drawings. In *Augmented and Virtual Reality: First International Conference, AVR 2014, Lecce, Italy, September 17-20, 2014, Revised Selected Papers 1* (pp. 421-427). Springer International Publishing.

30. Chalhoub, J., & Ayer, S. K. (2018). Using Mixed Reality for electrical construction design communication. *Automation in construction*, *86*, 1-10.

31. Dunston, P. S. (2009). Evaluation of augmented reality in steel column inspection. *Automation in Construction*, *18*(2), 118-129.

32. Wang, X. (2009). Augmented reality in architecture and design: potentials and challenges for application. *International journal of architectural computing*, *7*(2), 309-326.

33. Wang, X., & Dunston, P. S. (2013). Tangible mixed reality for remote design review: a study understanding user perception and acceptance. *Visualization in Engineering*, *1*, 1-15.

34. Thangaratinam, S., & Redman, C. W. (2005). The delphi technique. *The obstetrician & gynaecologist*, *7*(2), 120-125.

CHAPTER 2

Augmented Reality Applications for Synchronized Communication in Construction: A Review of Challenges and Opportunities

2.1 Publication Information

The text presented in this chapter was submitted for publication, accepted, and published in the International Journal of Applied Science under the title "Augmented Reality for Synchronized Communication in Construction: A Review of Challenges and Opportunities" (El Kassis et al., 2023).

2.2 Abstract

Many researchers in the construction field have explored the utilization of augmented reality (AR) and its impact on industry. Previous studies have shown potential uses for AR in the construction industry. However, a comprehensive critical review exploring the ways in which AR supports synchronized communication is still missing. This paper aims to fill this gap by examining trends identified in the literature and by analyzing both beneficial and challenging attributes. This work was performed by collecting numerous journal and conference papers, using keywords including “augmented reality”, “construction”, and “synchronous communication”. The papers were then categorized based on the reported attributes that were indicated to be challenges or benefits. Throughout the analysis, several benefits were consistently reported, including training, visualization, instantly sharing information, decision making, and intuitive interaction. Similarly, several challenges were consistently reported, such as difficulty in

manipulation, unfriendly interface, device discomfort, and sun brightness. Regarding other attributes, such as field of view, cost, safety hazards, and hands-free mode, researchers provided divergent reports regarding whether they were beneficial or detrimental to AR communication. These findings provide valuable guidance for future researchers and practitioners, enabling them to leverage AR for synchronized communication in ways that consistently offer value.

2.3 Introduction

The construction industry generates considerable economic activity and contributes to the growth of nations. The construction industry involves the coordination and the collaboration of a number of firms and organizations engaged in the process of building a facility. Despite the importance of this industry to the economy, it has historically been criticized for low productivity compared to other industries (*1*). Some of these productivity issues relate to the large number of stakeholders involved in a construction project and the communication process among them (*2*). A lack of innovation in the construction industry has been listed as one of the multiple reasons resulting in low productivity (*3*). This shows the importance of implementing new technologies that ease collaboration of all parties involved through effective communication mechanisms.

Augmented reality (AR) is one of the emerging technologies that can be used in the construction industry, which involves overlaying virtual objects on the existing real environment so that it appears as if they are both present at the same time (*4*). In the construction industry, AR has been explored in many fields including communication (*5*), visualization (*6*), inspection (*7*), and education (*8*). Communication is a method of exchanging information in real time or with a time lag between two or more parties (*9*). Asynchronous communication is a method of interaction that does not happen in real time (*10*).

To facilitate synchronized communication between an on-site user and an off-site user with AR, an online platform can be utilized (e.g., Microsoft Dynamics 365 Remote Assist*)*. This approach enables individuals in remote locations to communicate with each other using AR. Off-site users can elect to use traditional computers to create and view AR annotations, while field users can elect to use head-mounted displays (e.g., Trimble XR 10 and Lynx R-1) or handheld devices for AR interaction (*11*). Figure 1 represents a strategy for facilitating synchronous AR communication in order to illustrate the fundamental aspects of AR that support synchronous communication in the construction industry. This figure highlights how different types of users (top) may interact with different hardware (middle) through a common software (bottom) in order to support synchronous AR communication between on- and off-site individuals.

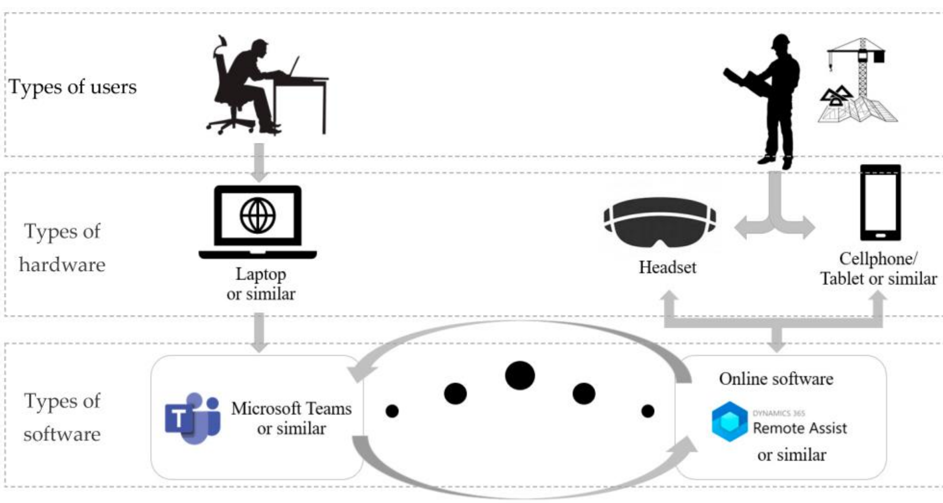


Figure 2. Off-site and On-site Users' Hardware and Software.

While there have been numerous studies that have explored the trends of using AR for asynchronized communication (*12, 14*), there is a noticeable gap in the literature regarding comprehensive reviews of trends specifically focusing on real-time communication (i.e., synchronized communication) across various contexts. Conducting such studies would greatly benefit practitioners by providing a deeper understanding of the advantages offered by AR for synchronized communication, the challenges encountered in its implementation, and the specific contexts where AR is most effective or needs to be approached with caution.

This study explores the literature on the topic of using AR for synchronized communication in order to answer the following two main questions:

(1) What attributes related to AR for synchronized communication are consistently reported by researchers to be either challenging or beneficial?

(2) For the attributes where researchers diverge in characterizing the benefits or drawbacks, what contextual elements within the papers differ in a manner that may contribute to the differing reports?

This paper aims to identify the contexts in which AR has been implemented for synchronized communication, while also examining the benefits and challenges reported by AR researchers in the industry. An understanding of this information is important and critical, especially since the application of AR in the construction industry is being constantly developed and different studies may show divergent trends. For example, some studies have mentioned challenges related to limited vision provided by the tools supporting AR, while others have disagreed and consider this challenge to be an opportunity to share a clear vision for the site. The results of this analysis of the literature will inform researchers to include or exclude contextual factors to gain or mitigate benefits or challenges when using AR for synchronized communication in the construction industry and will inform practitioners to mitigate the challenges that are consistently faced during the use of AR for synchronized communication.

2.4 Literature Review

Many researchers have reviewed the use of AR in the construction industry. These studies have explored the implementation of AR for specific uses, such as design review (*6*), exchange of information methods (*15*), construction inspections and monitoring applications (*16,17*), construction layout tasks (*18*), and construction activity visualization (*19*).

In order to understand the trends reported in previous studies among the different uses of AR, several studies have explored the state of knowledge around AR. For example, a critical review of academic publications that investigated how learning is different between AR and non-AR experience was conducted to provide a comprehensive understanding of how the medium of AR differs from other educational media (*20*). Chi et al. (2013) discussed trends in AR applications for architecture, engineering, construction, and facility management (AEC/FM) by summarizing the results of 101 research efforts, and they outlined the research trends and opportunities for applying AR focusing on four technologies, i.e., localization, natural user interface (NUI), cloud computing, and mobile devices (*21*). An AR literature study has also been conducted to provide a statistical review of the use of AR in the AEC industry offering construction practitioners and researchers an assessment of AR application including the purposes for which these technologies have been applied in different project phases from 1999 to 2012 (*22*). In addition, El Asmar et al. (2021) investigated the most common limitations and benefits reported by construction-related research publications using current generation AR technology (*12*). Moreover, a meta-analysis of AR challenges in the underground utility construction industry was conducted by Fenais et al. (2018) that aimed to make the construction industry aware of the benefits of leveraging AR to prevent utility strikes, while enhancing productivity (*23*). In 2020, Fenais et al. conducted a systematic review of AR applications in the industry to better understand the state-of-the-art of this technology in the underground construction field, and to identify challenges and barriers (*24*).

While these studies delved into the implementation of AR in the industry and the reported patterns, their focus may not have necessarily been on real-time, synchronous usage of AR in the field. This emphasizes the importance of gaining a deeper understanding of the influential factors that specifically impact AR applications in the construction industry, particularly in the context of synchronized communication.

Given the novelty of AR and the practical implications from testing unproven technologies on site, it seems logical that the majority of studies would focus on lab-based environments to test various aspects of AR prior to practical implementation. However, after testing AR in a controlled environment, several studies expressed the importance of AR testing on uncontrolled live construction sites where user performance was affected by site conditions such as noise, labor congestion, and safety concerns [18]. Testing the application in a real environment helps to evaluate the flexibility of AR leading to real improvements in performance and productivity. Chalhoub and Ayer

(2018) mentioned that the performance of the user was affected by site conditions (*18*). Cote et al. (2014) stated that investigating the development factors of 3D perception using AR in a construction context would be more valuable (*25*). Similarly, some studies have encouraged the need for future studies to be conducted on construction sites (*21*). The high percentage of AR studies conducted in controlled environments highlights the need to build on the findings of these studies and to explore AR research in uncontrolled environments in the construction industry. This highlights the necessity of comprehending the various types of environments and contextual factors that can impact the implementation of AR for communication in the construction industry.

2.5 Methodology

This research presents a comprehensive review of numerous journals and conference papers obtained from various sources. We applied a systematic review methodology for collecting and analyzing data from a number of research publications in the industry, following the processes described by Briner and Denyer (2012), and Denyer and Tranfield (2009) (*26,27*). To conduct this systematic review, we structured the method into the following three distinct phases: criteria selection, search and filtering, data collection and classification (*24*). The method employed is illustrated in Figure 2 and elaborated in the subsequent sections. The figure provides an overview of the process and highlights the criteria considered during the review.

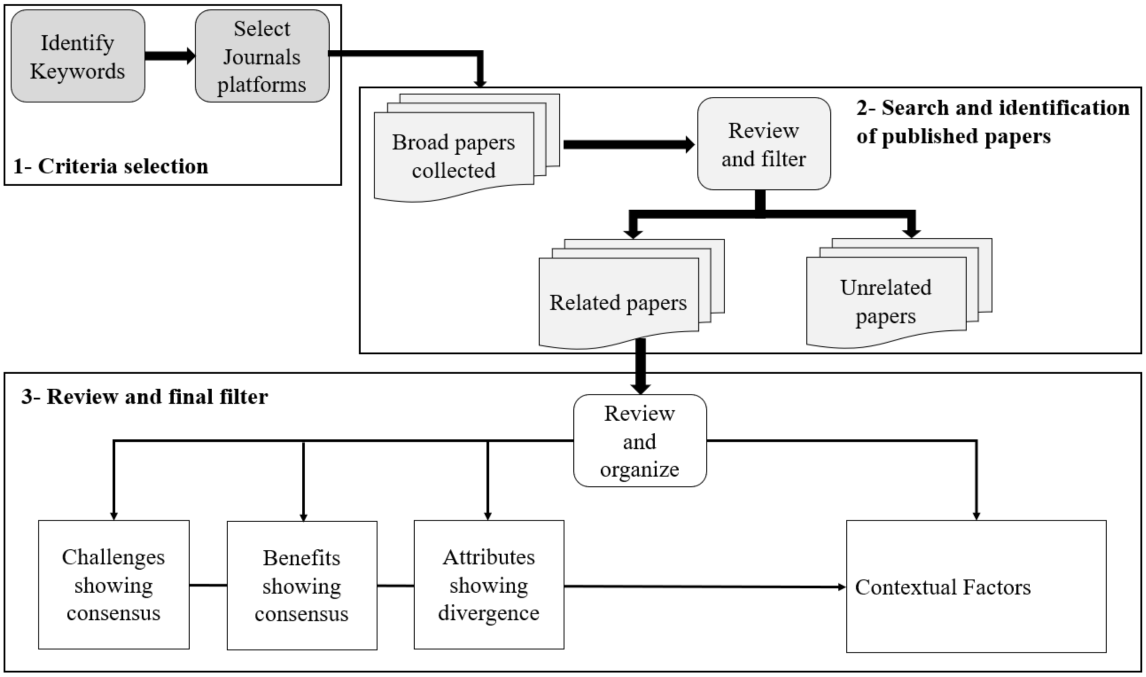


Figure 3. Research Method.

2.5.1 Criteria Selection

As an initial step, we identified the following three keywords highly related to the topic: “augmented reality” representing the technology in use, “construction” representing the field where this technology is applied, and “communication”. Limiting the research to these key words helped elicit the papers that were of interest to this study.

Next, we selected a number of journals and peer-reviewed conference proceedings related to the construction industry and augmented reality to ensure a large and comprehensive review. We targeted the following journals and conferences: M*ultidisciplinary Digital Publishing Institute (MDPI) Journal of Applied Science,* Journal of Information Technology in Construction (ITcon), Journal Automation in Construction, Journal of Computing in Civil Engineering, Journal of Construction

Engineering and Management, Journal of Management in Engineering, Journal of Computing and Information Science in Engineering, Visualization in Engineering, Advances in Civil Engineering, Advanced in Engineering Informatics, International Journal of Human–Computer Interaction, Organization Technology and Management in Construction, Journal of Infrastructures Systems, as well as proceeding from the Institute of Electrical and Electronics Engineers (IEEE) and the American Society of Civil Engineering (ASCE) Construction Research Congress (CRC). These journals and peer-reviewed conference proceedings are related to the construction industry and regularly include publications relevant to innovative construction strategies such AR.

2.5.2 Search and Identification of Published Papers

As a second step, we collected all the papers and conducted a more thorough review of each article to identify the studies directly relevant to synchronized communication. We carefully read the abstract, the objective, the methodology, and the conclusion sections of each paper to identify which studies were related to the main subject and which studies were not reporting on the use of AR for synchronous communication.

While reading these parts of the papers, we went through the cited references that had the same key words mentioned in the first phase. These cited references were reviewed using the same criteria as the papers initially identified using a keyword search. If papers pertained to the topic studied, they were included in the review. If they did not pertain to AR for synchronous communication, they were excluded. This process helped ensure that we identified relevant studies in the literature that may not have been identified in initial searches.

2.5.3 Review and Final Filter

As a third step, we categorized the papers based on the information that each paper offered. First, the papers were classified based on the type of environment in which the research was conducted, i.e., either in controlled environments (i.e., lab-based) or uncontrolled environments (i.e., construction site), based on the setting described in the paper. A controlled environment was defined as an enclosed space with precisely regulated environmental variables to meet operational needs; these variables could be temperature, light, pressure, and humidity (*28*). Conversely, an uncontrolled environment was a representation of the "real word" where unpredictable outdoor conditions and variational environments were left as they affected any ongoing situation (*29*). Then, the papers were classified by type of project, i.e., either horizontal, vertical, or academic research. Vertical projects include all construction structures that stretch vertically, for example, skyscrapers, towers, apartment buildings, office buildings, and other types of commercial buildings. Frequently referred to as heavy civil construction projects, horizontal projects are structures that stretch in length more than height, such as bridges, roads, highways, railroads, airfields, pipelines, and transit. Some academic studies did not relate to a specific construction project but included academic exploration through a survey, a questionnaire, university experiment, or AR implementation in lab-based environments.

The next classification of the papers focused on the documented challenges identified in relation to AR usage. We carefully recorded all the challenges mentioned throughout the papers and examined how frequently each challenge was cited by different sources. Similarly, the next classification examined the documented benefits of utilizing AR. Using a similar approach to the previous approach, we documented all the benefits identified in 59 papers and analyzed the number of times each benefit was mentioned.

Once the deep review of each paper was completed, each paper was classified by type of environment and type of project. In addition, challenges and benefits reported in each paper were grouped in one table with the number of times each attribute (challenge or benefit) was mentioned. In some cases, when a challenge or a benefit was reported only once but never repeated a second time by any other paper, the attribute was removed from the table considering that there was no consensus from more than one paper. In other cases, divergence was noted when the same attribute was reported as a challenge in a paper and a benefit in another paper. In these cases, we went back to the paper referencing the attribute and tried to understand the context and the type of project in which AR was used, to try to understand the reason behind the divergence. Once all attributes were identified and those that were reported more than once were noted, the results showed patterns for which there was consensus or divergence in attributes reported in the research.

2.6 Results and Discussion

We initially identified 171 papers through the keyword search. After reviewing the papers to determine relevance to AR for synchronized communication, 59 papers were identified for analysis. Table 1 shows the organization of the final list of collected papers by journal and conference venue.

Table 1. Journals Selected Before and After the Filter.

Journals	After Filtering
Automation in Construction	22
Journal of Applied Science	5
Journal of Computing in Civil Engineering	5
Journal of Information Technology in Construction (ITcon)	4
Visualization in Engineering	2
Advances in Civil Engineering	2
Advanced Engineering Informatics	2
International Journal of Human–Computer Interaction	2
Journal of Construction Engineering and Management	2
Journal of Management in Engineering	1
Journal of Computing and Information Science in Engineering	1
Organization, Technology and Management in Construction	1
Journal of Infrastructures System	1
Conferences	
Institute of Electrical and Electronics Engineers (IEEE)	7
Construction Research Congress (CRC)	2
TOTAL	59

After conducting a thorough review of the collected papers, the challenges and benefits associated with AR application in synchronized communication were extracted and classified, as summarized in Figure 3. While some attributes exhibited consensus across the papers, others displayed divergence. These discrepancies could be the results of contextual differences between projects or types of research projects. A number of challenges reported related directly to the type of device in use, AR application, and the environment surrounding the practitioner using AR. A total of twenty-four attributes were reported, with seven benefits and eleven challenges showing unanimous agreement among all the papers. However, six attributes demonstrated divergent findings within the existing literature.

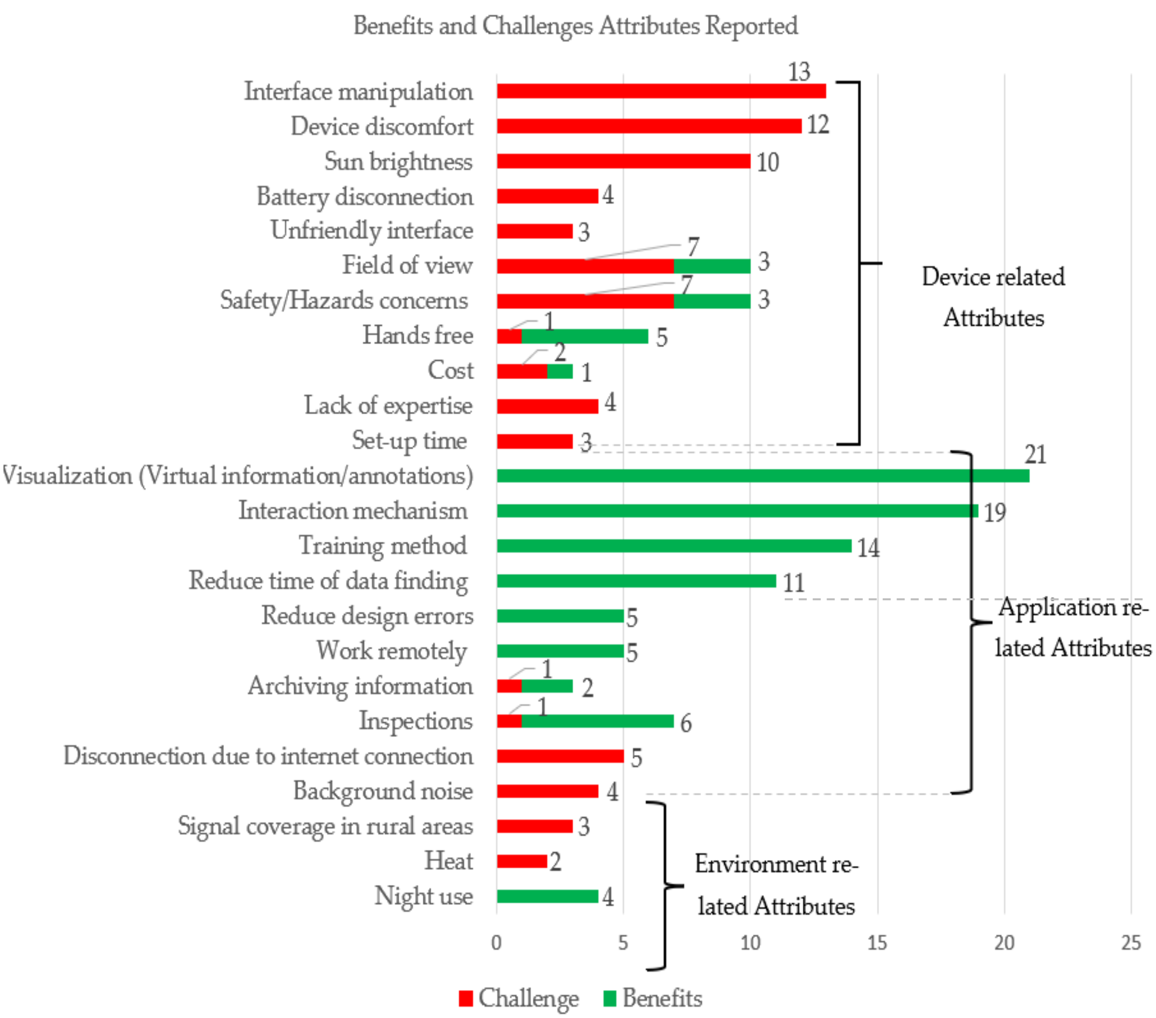


Figure 4. Number of Attributes (i.e., Benefits and Challenges) Showing Consensus/Divergence.

2.6.1 Consensus on Challenges

2.6.1.1 Interface Manipulation

Interface manipulation is a challenge that was highly reported in the review of these papers and showed consensus among 13 papers. Not all devices supporting AR are manipulated virtually and require gesture control; only head-mounted displays (i.e., headsets) require virtual manipulation. Research has reported that this manipulation is not easy (*30*, *32*). While implementing AR in a lab-based environment for multiscreen construction discussion, users reported that AR models (i.e., annotations and similar features) were hard to control (300. In addition, when implementing AR in uncontrolled environments (i.e., live construction sites), the virtual interface manipulation of a head-mounted device was reported to be complicated and not easy, especially when physically moving (*11*).

Although some papers mentioned that previous training provided to the users might ease the manipulation of the virtual interface and would provide a solution to overcome this challenge (*33, 35*), studies still identified this attribute as a challenge, since most researchers were implementing AR with new practitioners who had no previous experience using virtual manipulation or had no extensive training. Therefore, this challenge is directly related to the type of device and software in use.

2.6.1.2 Device Discomfort

Most of the collected papers reported the use of AR through the implementation of software in a headset device such as “Trimble XR10” and also reported a challenge related to the weight of the device on the head of the user (*19*,*33*,*34*,*36*,*37*). The weight is considered to be a considerable constraint of the device supporting the application, especially when using the device over a long period of time. Twelve papers reported the same attribute related to the device being uncomfortable which showed a consensus among them. Even though AR hardware and software are being consistently improved, the size of the hardware installed on the head is a challenge considering the incorporated hardhat needed to address safety and PPE requirements. Therefore, this challenge is related to the type of device in use.

2.6.1.3 Sun Brightness

Sun brightness was another challenge identified by ten papers. Implemented in a construction environment, users expressed concerns about the clarity of vision due to sun glare. In addition, even in controlled environments, researchers mentioned that the display platform of the AR virtual interface provided by head-mounted devices needed ambient to low lighting for the display to be more effective and that the use of an interactive hologram in outdoor environments could be challenging (*29*). However, some studies introduced low-cost solutions using crafted tinted films mask, to be installed on the front visor of the device to mitigate the limitations during daylight (*38*). Therefore, it seems that trials to overcome this challenge have been introduced and future research has the potential to address it. This challenge is related to the type of device in use since it is related only to head-mounted hardware supporting AR applications and may not be applicable to cellphones, tablets, and or similar hardware supporting AR applications.

2.6.1.4 Battery Disconnection

Disconnection of hardware physical components such as the battery was identified as a challenge by four papers. This challenge was mentioned considering the use of the application independent of site context and project type. Researchers mentioned that adapting to some requirements before the use of the devices (e.g., by making sure that the device is fully charged) could help overcome this challenge (*11*). Others suggested the use of power banks during AR application to ensure battery charging (*36*). This challenge is related to the type of hardware's battery, which may have implications for all types of AR devices (i.e., head-mounted displays, cell phones, and tablets).

2.6.1.5 Unfriendly Interface

The use of head-mounted displays was reported to be unfriendly, and practitioners were unfamiliar with these types of interfaces. Three papers mentioned that the interface could be more user friendly or customizable according to the user's needs (*19,30,36*). In a lab setting, students suggested that the user interface for the data-finding tasks offered by the virtual manipulation of a head-mounted device was not user friendly. Similar to a construction environment, users reported that the same interface could be more friendly, or custom-made for specific users. This interface is offered only when using a head-mounted device; AR applications supported by mobile hardware are different. The interface on mobile or pad devices is offered through the screen and manipulation through finger touch movements. Therefore, some studies reported that, with training and practice, users could become more familiar with the gesture interface offered by the head-mounted device which helped in overcoming this challenge (*34,35*). This attribute is related to the type of device in use supporting the application.

2.6.1.6 Lack of Experience

Lack of experience was a challenge related to AR application that was identified by four papers. As mentioned earlier, AR highly depends on virtual manipulation. Researchers have reported that this manipulation in addition to the interface constitutes challenges, thus practice and experience is needed. Independent of any contextual factor, this challenge is related to the practitioners using AR, their use cases, and how much they are exposed to the technology. Recommendations were provided in some studies suggesting training sessions and practice to overcome this challenge.

2.6.1.7 Set-Up Time

Set-up time was reported to be a challenge related to the application as well as how much time is needed to set up the hardware, power it on, run the software, and use the application the way it is intended to be used. AR applications require previous preparation. For example, 3D models need to be previously drawn using other software in order to be incorporated during a visualization application. Therefore, this challenge is related to the development of the application. Users need guidelines and instructions to guide them on what to prepare and how to set up and use this application, so they become more familiar with the software and the hardware (head-mounted displays, cellphones, and tablets) and ease its implementation.

2.6.1.8 Environment Related Challenges

AR implementation highly depends on an internet connection. Signal coverage in rural areas is a challenge that is crucial for the AR application, and without it, no synchronized communication between stakeholders can occur (*35,39*). Other weather and environmental issues have been reported to affect the use of AR, for example, noise and heat. Although these challenges seem to have been encountered in real time during one uncontrolled environment study, they were, in fact, also mentioned in other papers.

2.6.2 Consensus on Benefits

There were a number of challenges for AR implementation that were consistently reported among the identified papers, but there were also several beneficial attributes that demonstrated the effectiveness of AR in construction research for communication. These reports showed the potential of AR and the opportunities that AR supports in the industry. The following sections review the seven main benefits for which there is consensus in the literature about AR.

2.6.2.1 Visualization

Seventeen papers agreed that the use of AR application for communication enabled the visualization of information and site activities. This visualization can be achieved through various devices such as head-mounted displays, cellphones, or tablets that support AR applications. Within an uncontrolled environment, Lin et al. (2019) mentioned that AR provided better visualization results which allowed the users to interact with reality more intuitively (*40*). In addition, visualization of the site helps in understanding and preventing design issues and monitoring construction activities (*41*). This shows the advantage of AR for exchanging information in real time to provide the experience of site visits and in-person meetings in addition to the verbal conversion and discussion needed on site. Therefore, this benefit is related to the AR application, independent of the type of environment and type of project.

2.6.2.2 Interaction Mechanism

Nineteen papers mentioned that AR application is an interaction mechanism between different parties. Within a construction environment, on-site users can communicate with off-site users allowing for a natural flow of information (*11*,*30*). It has also been mentioned that this interaction mechanism can be conducted with multiple people at the same time allowing for better collaboration (*42*). In addition, mobile AR and head-mounted AR create a context-immersive space that facilitates social interactions among users, construction places, and objects, and provide multi-user-based contents in the linked structure (*42*). Therefore, the papers suggest that there is consensus about the beneficial aspect of AR being an interaction tool that allows for a visual experience between users to communicate verbal and contextual information of the site, allowing for collaborative decision making.

2.6.2.3 Training Method

Fourteen papers agreed that AR application helped in training personnel and referred to AR as a learning and educational tool. Hou et al. (2013) mentioned that using AR for communication helped to improve the learning curve of trainees significantly, and fewer errors were made on site (*42*). In addition, AR eased the transferability of knowledge between the participants in the learning activities (*43*). Regardless of the type of device in use (i.e., head-mounted displays, cellphones, or tablets), the type of environment, or the type of project an application is being implemented in, this benefit does not depend on other contextual factors, based on the literature. This highlights the importance of AR in sharing information and expanding knowledge through communication in the industry, especially, since all the identified papers agreed on this topic.

2.6.2.4 Reduce Time of Data Finding

Reducing time of data finding was a benefit reported with consensus by 11 papers. This data finding ability that AR offers reduces wasted time and enhances the flow of information (*30*,*44*). Finding building elements without looking at maps or complex 3D models is considered to be time saving (*45*). In addition, Kim et al. (2013) stated that AR had a positive impact on site monitoring, task management, and real-time information sharing (*44*). AR improves the performance of existing on-site management processes and gives direct access to project information databases resulting in finding the location of construction resources on site without any time-consuming effort. Therefore, AR application offers the benefits of quick access to soft data and reduces the time for data searching regardless of the type of device in use. Having a consensus between a number of papers on this benefit highlights the potential of AR during communication use cases for inspections and sharing of information.

2.6.2.5 Reduce Design Errors

Five papers reported that AR application for communication helped to reduce design errors. Within the construction context, AR applications have been developed to combine virtual object information with real elements. This visualization of construction information results in better coordination and an easier understanding among project stakeholders. Kim et al. (2013) stated that using AR visualization was expected to help reduce design and construction errors in advance and to reduce the time taken to select an optimized construction method and structure element (*44*). Reducing design errors prior to the start of construction helps save cost and change orders to resolve those errors. In addition, the time needed to answer requests for information (RFIs) during the construction process is expected to be reduced when using AR to find design errors. AR for communication using visualization is a benefit that demonstrated a consensus among many papers.

2.6.2.6 Work Remotely

Working remotely without spending time traveling to the site is another advantage of AR application. Five research papers reported that AR allowed site quality managers and trade managers to inspect construction works from the office without visiting the site (*35*,*36*,*46*,*48*). This highlights the importance of communication supported by AR in the construction industry. Whatever the contexts of the users or the type of project in which the study has been conducted, researchers showed consensus about these benefits reported during the use of AR for communication.

2.6.2.7 Night Use

AR application for communication purposes is not only used during daylight; four reports mentioned that AR could be used during dark hours (*11*,*30*). This attribute is related to the surroundings of the practitioner. Therefore, this benefit is related to the environment of the user. The consensus shown among the papers and the low number of papers (four) reflecting this consensus is arguably a product of the small number of studies conducted in uncontrolled environments during dark hours using both head-mounted displays and handheld mobile devices.

2.6.3 Divergence of Attributes

While the previous findings show consensus among the papers, we also collected attributes for which there were differences in findings among papers. In this section, we describe attributes that were viewed as beneficial attributes in some papers, while in other papers they were identified as a challenge.

2.6.3.1 Field of View

The field of view provided by the frame of the visor of a head-mounted device and the resolution of the shared picture were challenges reported in the literature by six studies (*18*,*31*,*32*,*34*,*36*,*49*). These six studies were conducted in lab-based environments. Conversely, two other studies that reported positive results were conducted in different contexts. El Kassis et al. (2022) and El Ammari and Hammad (2019) both reported positive results related to the field of view. El Kassis et al. (2022) stated that based on the perception of on-site and off-site users, the shared vision of the site through the use of Trimble XR10 (version of HoloLens-2 incorporated in a hard hat) was clear and that the device had the ability to share exactly what the on-site user is viewing and looking at (*35*).

It is noteworthy to mention that reviewing 59 papers as part of this analysis of the literature, the authors found that 72% of the studies were conducted in controlled environments, whereas only 28% were conducted in uncontrolled environments. El Kassis et al. (2022) implemented AR in live construction sites and Ammari and Hammad (2019) developed AR applications in controlled environments but then applied them in a real environment (*35*,*45*). While the field of view seems to be related intuitively to the type of device in use (i.e., mobile vs. head-mount device), in the case of communication, this attribute was also related to the type of environment in which a study was conducted. Within the construction context, the purpose of using AR and the field of view that needs to be shared is wider than when using AR in controlled environments where the vision can focus on a defined object or area. This divergence indicates that the vision transferred by the device during an AR application is highly affected by the surrounding of the users performing the call and the goals of using AR for the project at hand.

2.6.3.2 Safety/Hazards Concerns

Seven papers reported safety concerns when implementing AR on construction sites (*30*,*36*,*45*,*46*,*49*,*50*). Although some of these papers recommended training to overcome this challenge (*48*), other papers showed variance and considered that no safety/hazardous issues were faced during AR application for synchronized communication on site (*10*,*51*). Reviewing the context and the type of project during which each paper recorded these findings, only one paper among the seven papers that reported that safety was a challenge was conducted in a real environment (*45*). This study implemented AR in a real environment to facilitate the communication of site issues related to thermostats, showing no movement for the user during the application. Moreover, regarding the two studies that considered that no safety issues were faced during AR application, one study was conducted in an uncontrolled environment (*10*), while the second study was conducted in a controlled environment (*51*). The only difference between these papers was the type of project studied; one paper studied AR in a vertical project (i.e., a 10-story building) (*51*) whereas the second paper studied AR in horizontal road infrastructure work (*10*). This indicates that safety issues affecting the use of AR devices could be related to the type of projects and the movement of the practitioner while using AR.

2.6.3.3 Hands-Free Mode

Hands-free mode is another attribute that showed divergence among papers. Having one's hands free during an AR call is a benefit mentioned by five papers (*13,31,32,35,38*); these papers implemented AR for communication in different environments (both controlled and uncontrolled) and for different types of projects or applications (i.e., infrastructure and academic research). Conversely, Ammari and Hammad (2019) stated that AR modules could not be used in hands-free mode (*45*). The literature provides a variation in the results. The five papers that reported a benefit used head-mounted devices supporting AR, whereas Ammari and Hammad (2019) used a tablet (*45*). Therefore, and to no surprise here, there is a consensus among the papers that the type of the device in use (head-mounted versus tablet) is related to considering this item a benefit or a challenge, supporting the premise of this literature analysis paper in which we are analyzing the findings of various studies around this same topic and identifying the contexts in which these findings are made.

2.6.3.4 Cost

Two studies agreed that the cost of the equipment and overall implementation cost of AR in the construction industry pose a challenge (*36*,*37*); however, Kim et al. (2013) reported an opposite finding (*44*). Upon comparing these three papers, we found that the type of devices used by Kim et al. (2013) was a head-mounted AR device (example, HoloLens-2), whereas the other papers used an AR module embedded in a smartphone. It is not surprising that the cost of using an existing smartphone is relatively not as much of a challenge compared to other types of devices, also considering that a smartphone would already be available with most personnel working on site. This indicates that “cost” is another attribute that is directly related to the type of device in use.

2.6.3.5 Archiving Information

Two papers identified the ability to archive information after AR calls and that archiving the information exchanged was a benefit related to the application (*38,52*). However, Delgadoa et al. (2020) mentioned that archiving the outcomes of an AR call was difficult (*36*). The reports were different and showed a variation in the outcomes. When examining the differences among these papers, we noticed that these three papers were conducted in different contexts. First, the study by El Kassis et al. (2022) was conducted in an uncontrolled environment, while the other two studies were conducted in controlled environments (*38*). Second, the information reported in the study by Patil et al.

(2020) were based on a finding reported by a different research study and not explored by the study itself (*52*). Third, the findings by Delgadoa et al. (2020) were reported based on a series of exploratory workshops and questionnaires (*36*). This might be the result of simply not being able to explore the application to its maximum since users were novice and not familiar with the application. Therefore, the ability to archive information without facing difficulties needs experienced practitioners and could be the subject of future research.

2.6.3.6 Inspections

Conducting inspections is a critical activity in the construction of any project. It typically involves significant time spent on traveling to the site, accessing relevant information, and sometimes consulting with other experts (*53*). The ability to conduct inspections using AR for communication might ease the challenges related to the inspector or engineer's physical presence. Several papers mentioned that AR application could facilitate inspections (*10,17,35,45,47,54*). However, Harikrishnan et al. (2021) mentioned that not all types of inspections could be conducted using AR, specifying that complex and in-depth inspections still needed a physical presence on site (*46*). By reviewing the context of each paper, we noticed that in-depth inspections were mentioned as a challenge only when interviewing experts through a questionnaire (*46*), whereas the remaining papers that mentioned using AR to conduct inspections was a benefit were conducted in uncontrolled environments (*10,17,35,45,47,54,55,56*) where practitioners used AR on site (*57*). Although exploring the perceptions of future users is important, this does not mean that their insights are 100% true and might not change while implementing the application (*58,59*). This indicates that conducting inspections using AR is independent of the contexts in which the user exists in.

2.7 Limitations

This study provides valuable insights into the observed trends in reports about AR in the construction industry. However, it is important to acknowledge the inherent limitations of this work. One limitation arises from the focus on the technological development of AR over a 10-year period, specifically examining papers published during this time that address AR for communication in construction tasks. Such limitations are expected when exploring emerging technologies that are still in their early stages of adoption. Additionally, it is important to consider that other domains may have reported diverse benefits and challenges associated with AR performance, extending beyond a simple examination of advantages and limitations. It is also worth noting that attributes mentioned 10 years ago may have since been resolved, which would make them no longer relevant to the use of modern AR technology. While reports from other fields could potentially validate or raise questions about the findings of this construction-centered study, they were intentionally excluded due to the defined scope of the paper. Therefore, while the observed trends in this study may not encompass all possible viewpoints, they effectively illustrate the general trends found within the published research on the construction industry. These trends can serve as a valuable foundation for guiding future studies and providing them with evidence derived from recent AR works in the construction domain.

2.8 Conclusions

This paper provides a systematic analysis of the literature on the use of augmented reality (AR) for synchronized communication in the construction industry. It identified and analyzed trends related to the type of environment as well as the type of project that the studies were conducted in, and also identified challenges and benefits reported while implementing this technology. We identified eleven challenges, seven benefits, and six additional attributes that could be either a benefit or a challenge depending on the context. Several contextual attributes related to how AR was implemented were identified, related to the type of environment in which each study was conducted, the type of project, the activity of the practitioner, the type of the device in use, the year in which the study was completed which reflected the development of the application, and the experience of the user. Future AR developers and researchers should build on the identified benefits, challenges, and contextual factors to strategically incorporate or avoid certain settings during AR implementation and to maximize the beneficial aspects of AR that have been reported in the literature.

References

1. Gamil, Y.; Abdul Rahman, I. Identification of Causes and Effects of Poor Communication in Construction Industry: A Theoretical Review. Emerg. Sci. J. 2017, 1, 239–247.

2. Emmitt, S.; Gorse, C. Communication in Construction Teams; Taylor & Francis eLibra: Abingdon, UK, 2006.

3. Gann, D.M. Building Innovation: Complex Constructs in a Changing World; Thomas Telford Publications: London, UK, 2000.

4. Azuma, R.T.A. Survey of Augmented Reality. Presence Teleoperators 155 Virtual Environments. 1997, 6, 355–385.

5. Bae, H.; Golparvar-Fard, M.; White, J. High-precision vision-based mobile augmented reality system for context-aware architectural, engineering, construction and facility management (AEC/FM) applications. Vis. Eng. 2013, 1, 3. Available online: http://www.viejournal.com/content/1/1/3 accessed on 09 November 2022.

6. Wang, X.; Dunston, P.S. User perspectives on mixed reality tabletop visualization for face-to-face collaborative design review. Autom. Constr. 2008, 17, 399–412.

7. Moreu, F.; Lippitt, C.; Maharjan, D.; Aguero, M.; Yuan, X. Augmented Reality Enhancing the Inspections of Transportation Infrastructure: Research, Education, and Industry Implementation; Transportation Consortium of South-Central States, University of New Mexico; New Mexico, 2019.

8. Wang, T.-K.; Huang, J.; Liao, P.-C.; Piao, Y. Does Augmented Reality Effectively Foster Visual Learning Process in Construction? An Eye-Tracking Study in Steel Installation. Adv. Civ. Eng. 2018, 2018, 2472167. https://doi.org/10.1155/2018/2472167.

9. Hull, D.M.; Saxon, T.F. Negotiation of meaning and co-construction of knowledge: An experimental analysis of asynchronous online instruction. Comput. Educ. 2009, 52, 624–639.

10. Kim, K.; Kim, H.; Kim, H. Image-based construction hazard avoidance system using augmented reality in wearable device. Autom. Constr. 2017, 83, 390–403.

11. Kassis, R.E.; Ayer, S.K.; Asmar, M.E.; Tang, P. Discovering Factors that Influence the Use of Augmented Reality for Communication on Active Highway Construction Sites. Transp. Res. Rec. 2022, 2677, 03611981221131311.

12. El Asmar, G.P.; Chalhoub, J.; Ayer, K.S.; Abdallah, A.S. Contextualizing Benefits and Limitations Reported for Augmented Reality in Construction Research. J. Inf. Technol. Constr. 2021, 26, 720–738. https://doi.org/10.36680/j.itcon.2021.039.

13. Kim, D.; Choi, Y. Applications of smart glasses in applied sciences: A systematic review. Appl. Sci. 2021, 11, 4956.

14. Diao, P.H.; Shih, N.J. Trends and research issues of augmented reality studies in architectural and civil engineering education—A review of academic journal publications. Appl. Sci. 2019, 9, 1840.

15. Datcu, D.; Cidota, M.; Lukosch, H.; Lukosch, S. On the Usability of Augmented Reality for Information Exchange in Teams from the Security Domain. IEEE Jt. Intell. Secur. Inform. Conf. 2014, 160–167. DOI: 10.1109/JISIC.2014.32

16. Zollmann, S.; Hoppe, C.; Kluckner, S.; Poglitsch, C.; Bischof, H.; Reitmayr, G. Augmented Reality for Construction Site Monitoring and Documentation. Proc. IEEE 2014, 102, 137–154.

17. Zhou, Y.; Luo, H.; Yang, Y. Implementation of augmented reality for segment displacement inspection during tunneling construction. Autom. Constr. 2017, 82, 112–121.

18. Chalhoub, J.; Ayer, S.K. Using Mixed Reality for electrical construction design communication. Autom. Constr. 2018, 86, 1–10.

19. Wang, X.; Dunston, P.S. Tangible mixed reality for remote design review: A study understanding user perception and acceptance. Vis. Eng. 2013, 1, 8.

20. Radu, I. Augmented reality in education: A meta-review and cross-media analysis. Pers. Ubiquitous Comput. 2014, 18, 1533–1543.

21. Chi, H.L.; Kang, S.C.; Wang, X. Research trends and opportunities of augmented reality applications in architecture, engineering, and construction. Autom. Constr. 2013, 33, 116–122.

22. Rankohi, S.; Waugh, L. Review and analysis of augmented reality literature for construction industry. Vis. Eng. 2013, 1, 9.

23. Fenais, A.; Smilovsky, N.; Ariaratnam, S.T.; Ayer, S.K. (2018, March). A meta-analysis of augmented reality challenges in the underground utility construction industry. In Proceedings of the Construction Research Congress 2018, New Orleans, LA, USA, 2–4 April 2018; pp. 80–89.

24. Fenais, A.S.; Ariaratnam, S.T.; Ayer, S.K.; Smilovsky, N. A review of augmented reality applied to underground construction. J. Inf. Technol. Constr. 2020, 25, 308–324.

25. Côté, S.; Beauvais, M.; Girard-Vallée, A.; Snyde, R. A Live Augmented Reality Tool for Facilitating Interpretation of 2D Construction Drawings; In Augmented and Virtual Reality: First International Conference, AVR 2014, Lecce, Italy, September 17-20, 2014, Revised Selected Papers 1 (pp. 421-427). Springer International Publishing. https://doi.org/10.1007/978-3-319-13969-2_32.

26. Briner, R.B.; Denyer, D. Systematic review and evidence synthesis as a practice and scholarship tool. In Handbook of Evidence-Based Management: Companies, Classrooms and Research; Oxford University Press: Oxford, UK, 2012; pp. 112–129.

27. Denyer, D.; Tranfield, D. Producing a systematic review. In The SAGE Handbook of Organizational Research Methods; SAGE: London, UK, 2009.

28. Bellare, J.; Davis, H.T.; Scriven, L.E.; Talmon, Y. Controlled environment vitrification system: An improved sample preparation technique. J. Electron Microsc. Tech. 1988, 10, 87–111.

29. Aghajanian, J.; Prince, S. Face Pose Estimation in Uncontrolled Environments. In Proceedings of the British Machine Vision Conference, London, UK, 7–10 September 2009; Volume 1, p. 3.

30. Lin, T.H.; Liu, C.H.; Tsai, M.H.; Kang, S.C. Using augmented reality in a multiscreen environment for construction discussion. J. Comput. Civ. Eng. 2015, 29, 04014088.

31. Chen, Y.C.; Chi, H.L.; Kang, S.C.; Hsieh, S.H. Attention-based user interface design for a tele-operated crane. J. Comput. Civ. Eng. 2016, 30, 04015030.

32. Tayeh, R.; Issa, R.R. Interactive holograms for construction coordination and quantification. J. Manag. Eng. 2020, 36, 04020079.

33. Chalhoub, J.; Ayer, S.K.; Ariaratnam, S.T. Augmented reality for enabling un-and under-trained individuals to complete specialty construction tasks. J. Inf. Technol. Constr. 2021, 26, 128–143.

34. Wu, W.; Sandoval, A.; Gunji, V.; Ayer, S.K.; London, J.; Perry, L.; Patil, K.; Smith, K. Comparing traditional and mixed reality-facilitated apprenticeship learning in a wood-frame construction lab. J. Constr. Eng. Manag. 2020, 146, 04020139.

35. El Kassis, R.; Ayer, S.K.; El Asmar, M.; Tang, P. Augmented Reality Communication on Active Construction Sites: A Pilot Study Exploring Non-Technological Factors. In Proceedings of the Construction Research Congress 2022, Arlington, Virginia, 9–12 March 2022; pp. 1202–1211.

36. Delgado JM, D.; Oyedele, L.; Demian, P.; Beach, T. A research agenda for augmented and virtual reality in architecture, engineering and construction. Adv. Eng. Inform. 2020, 45, 101122.

37. Davila Delgado, J.M.; Oyedele, L.; Beach, T.; Demian, P. Augmented and virtual reality in construction: Drivers and limitations for industry adoption. J. Constr. Eng. Manag. 2020, 146, 04020079.

38. El Kassis, R.; Ayer, S.K.; El Asmar, M.; Tang, P. Defining factors that support or hinder commercially available augmented reality (AR) devices for construction communication. In Proceedings of the Computing in Civil Engineering 2021, Orlando, FL, USA, 12–14 September 2021; pp. 1302–1310.

39. Chen, K.; Chen, W.; Li, C.T.; Cheng, J.C. A BIM-based location aware AR collaborative framework for facility maintenance management. J. Inf. Technol. Constr. 2019, 24, 360–380.

40. Lin, J.R.; Cao, J.; Zhang, J.P.; van Treeck, C.; Frisch, J. Visualization of indoor thermal environment on mobile devices based on augmented reality and computational fluid dynamics. Autom. Constr. 2019, 103, 26–40.

41. Soria, G.; Ortega Alvarado, L.M.; Feito, F.R. Augmented and virtual reality for underground facilities management. J. Comput. Inf. Sci. Eng. 2018, 18, 041008.

42. Hou, L.; Wang, X.; Bernold, L.; Love, P.E. Using animated augmented reality to cognitively guide assembly. J. Comput. Civ. Eng. 2013, 27, 439–451.

43. Dinis, F.M.; Guimarães, A.S.; Carvalho, B.R.; Martins, J.P.P. Virtual and augmented reality game-based applications to civil engineering education. In Proceedings of the 2017 IEEE Global Engineering Education Conference (EDUCON), Athens, Greece, 25–28 April 2017; IEEE: Piscataway, NJ, USA, 2017; pp. 1683–1688.

44. Kim, M.J. A framework for context immersion in mobile augmented reality. Autom. Constr. 2013, 33, 79–85.

45. El Ammari, K.; Hammad, A. Remote interactive collaboration in facilities management using BIM-based mixed reality. Autom. Constr. 2019, 107, 102940.

46. Harikrishnan, A.; Abdallah, A.S.; Ayer, S.K.; El Asmar, M.; Tang, P. Feasibility of augmented reality technology for communication in the construction industry. Adv. Eng. Inform. 2021, 50, 101363.

47. Kwon, O.S.; Park, C.S.; Lim, C.R. A defect management system for reinforced concrete work utilizing BIM, image-matching and augmented reality. Autom. Constr. 2014.

48. Hou, L.; Chi, H.L.; Tarng, W.; Chai, J.; Panuwatwanich, K.; Wang, X. A framework of innovative learning for skill development in complex operational tasks. Autom. Constr. 2017, 83, 29–40.

49. Fenais, A.; Ariaratnam, S.T.; Ayer, S.K.; Smilovsky, N. Integrating geographic information systems and augmented reality for mapping underground utilities. Infrastructures 2019, 4, 60.

50. Li, X.; Yi, W.; Chi, H.L.; Wang, X.; Chan, A.P. A critical review of virtual and augmented reality (VR/AR) applications in construction safety. Autom. Constr. 2018, 86, 150–162.

51. Yeh, K.C.; Tsai, M.H.; Kang, S.C. On-site building information retrieval by using projection-based augmented reality. J. Comput. Civ. Eng. 2012, 26, 342–355.

52. Patil, K.R.; Ayer, S.K.; Wu, W.; London, J. Mixed reality multimedia learning to facilitate learning outcomes from project-based learning. In Proceedings of the Construction Research Congress 2020: Computer Applications, Tempe, Arizona, 8–10 March 2020; American Society of Civil Engineers: Reston, VA, USA, 2020; pp. 153–161.

53. Ahmed, S. A review on using opportunities of augmented reality and virtual reality in construction project management. Organ. Technol. Manag. Constr. Int. J. 2018, 10, 1839–1852.

54. Meža, S.; Turk, Ž.; Dolenc, M. Component based engineering of a mobile BIM-based augmented reality system. Autom. Constr. 2014, 42, 1–12.

55. Vidal-Balea, A.; Blanco-Novoa, O.; Fraga-Lamas, P.; Vilar-Montesinos, M.; Fernández-Caramés, T.M. Creating collaborative augmented reality experiences for industry 4.0 training and assistance applications: Performance evaluation in the shipyard of the future. Appl. Sci. 2020, 10, 9073.

56. Lee, J.G.; Seo, J.; Abbas, A.; Choi, M. End-Users' augmented reality utilization for architectural design review. Appl. Sci. 2020, 10, 5363.

57. Diao, P.H.; Shih, N.J. BIM-based AR maintenance system (BARMS) as an intelligent instruction platform for complex plumbing facilities. Appl. Sci. 2019, 9, 1592.

58. Criollo-C, S.; Abad-Vásquez, D.; Martic-Nieto, M.; Velásquez-G, F.A.; Pérez-Medina, J.L.; Luján-Mora, S. Towards a new learning experience through a mobile application with augmented reality in engineering education. Appl. Sci. 2021, 11, 4921.

59. Chung, S.; Cho, C.S.; Song, J.; Lee, K.; Lee, S.; Kwon, S. Smart facility management system based on open bim and augmented reality technology. Appl. Sci. 2021, 11, 10283.

CHAPTER 3

Discovering the Factors that Influence the Use of Augmented Reality for Communication

3.1 Publication Information

The text presented in this chapter was submitted for publication, accepted, and published in the International Journal of Transportation Research Record under the title " Discovering Factors that Influence the Use of Augmented Reality for Communication" (El Kassis et al., 2022).

3.2 Abstract

The construction industry requires effective communication between project stakeholders in various locations. This communication can be facilitated by in-person site visits or phone calls. However, these methods can lead to wasted travel time or omitting critical visual site details, respectively. In theory, Augmented Reality (AR) can support consistent understandings of site environments similar to in-person visits but with the efficiency of phone calls. However, most studies exploring AR for communication in construction have done so in controlled environments. This work investigates the efficacy of AR calls in uncontrolled settings (i.e., active construction sites) by interviewing and recording practitioners who are using AR, in order to identify behaviors and perceptions that influence communication efficiency and effectiveness. The authors conducted qualitative analyses and identified 14 factors that can impact information exchanges between professionals using AR. The factors found in this study include: virtual manipulation; visual aids; shared action plan; hands-free operation; decision-making; site

interaction; working remotely; repetition; locomotion; performing different job types; device discomfort; background noise; lighting conditions; and disconnection in hardware physical and feature components. Some factors represent beneficial opportunities for AR, while others pose challenges. Some of the identified challenges may be resolved through technological innovations and user training, as discussed in the paper. Furthermore, this work provides evidence of factors for which current AR technologies are sufficiently developed to guide near-term implementation in practice.

3.3 Introduction: The Need for Effective Communication

The construction industry constitutes about half of the gross capital and three to eight percent of the Gross Domestic Product (GDP) in most countries (*1*). Despite the impact of this industry, it has been criticized for poor production, often due to challenges with communication (*2*,*3*). These production problems can take the form of time and cost overruns, legal disputes, and project failures (*2*). Part of the challenge for the construction industry is that the products built are rarely the same from project to project, and the teams of professionals assembled to design, engineer, construct, and operate the built infrastructure are also rarely the same. In construction, communication is a key management and leadership competency, especially since decision-making for these unique projects is based on effective communication (*4*). Communication is an essential component in building processes and a critical enabler to synergy and cooperation between all design and construction parties (*5*). These facts highlight the need for effective communication to allow informed decision-making that will support the outputs produced in this impactful industry (*4*,*6*).

Effective communication enables diverse project stakeholders to coordinate their actions, intentions, and collective understanding of the project (*7*). Communication is often facilitated through site visits and phone calls (*8*). In highway projects, efficient communication can build trust between stakeholders and reduce misunderstandings that lead to construction delays and rework. It can also reduce travel time, traffic congestion, and cost (*9*). Traditional methods of communication have some benefits but also some inherent drawbacks. Face-to-face communication during site visits allows for a natural mode of communication that enables all project participants to physically explore a site to understand relevant constraints. While this may support situations where being on-site is beneficial, it may lead to unnecessary time spent by stakeholders driving to and from remote sites. Conversely, phone calls and verbal exchanges with limited visual context could lead to misinterpretation of site details and, consequently, poor decision-making in some instances. In addition to logistical considerations, the impacts of poor communication have also been explored by researchers who identified 33 causes such as "Lack of effective communication between construction parties, lack of effective communication systems and platforms, improper communication channels, technology malfunction, lack of appropriate communications medium, inaccessibility of information, slow information flow between parties, inaccurate delivery of project information, unavailability of information at the time of need, and lack of understanding between parties" and 21 effects such as "time and cost overruns" (*2)*. These reports highlighting the need for effective and efficient communication motivate this work to explore new communication tools that simultaneously allow for verbal discussion and effective visualization of a site's context.

Augmented Reality, which is a subset of Mixed Reality (MR) (*10*), is a technology that allows users to see the real world with virtual objects superimposed upon or composed with the real world (*11*). In a highway construction context, AR can enable on-site and off-site users to see a consistent version of a construction site with a relevant model, drawing, or other text/arrow annotations superimposed onto the view of the space (*12)*. AR provides real-time and spatially relevant information to be communicated by participants in remote locations without physically traveling to construction sites. Theoretically, this provides an opportunity for AR to support the benefits of in-person site meetings with the efficiency of phone calls. In addition, AR may have the opportunity to resolve poor communication causes by offering an effective communication platform using remote virtual software, access to virtual information, direct flow of information between construction parties, accurate site information due to live visuals, and enhancing effective communication between parties.

The potential for AR to support communication has spurred a number of researchers to explore the viability of this technology in the construction domain. Many studies explored the use of AR in controlled environments such as design visualization (*13*), design review (*14*, *15*) and speeding up assembly processes (*16*,*17*). While these studies break new ground and illustrate the potential for this technology in construction, the controlled settings in which their findings were generated do not fully replicate the uncontrolled nature of active construction sites. There is a need to build on this work and better understand how AR supports construction communication in practice, where many uncontrolled factors could emerge while construction is ongoing. This paper aims to address this knowledge gap by investigating the factors that affect AR communication in real project site conditions.

The objective of this paper is to determine factors that could potentially impact the success of using AR for communication on active construction sites. The factors identified will be organized into categories related to technology, people, process, and environment. This list of factors will help document how subsequent research may address practical industry needs. The contribution of this work will guide academic research and practical adoption of similar emerging tools in the construction industry.

3.4 Background and Literature Review

Many construction researchers have explored the use of AR and its impact on the industry. The following examples will show some of its potential benefits, based on a comprehensive review of the literature on the topic. Safety is one aspect of construction that benefits from AR. During the daily progress of a construction project, the dynamic and congested nature of the site can lead to safety incidents. AR can introduce a vision-based hazard avoidance system that can improve workers' safety and inform them of potentially dangerous situations (*18*). AR offers potential in upgrading the communication between project managers and workers in real-time site execution, which increases workers' risk perception, resulting in improvement of determination of site safety risks (*19*). Inspection is another activity in the industry that can take advantage of AR. AR enables accurate field assessment and inspections by supporting managers to make better-informed decisions using various software applications as inspection tools for bridges and bridge management (*20*). Researchers studied innovative solutions for intelligent systems based on AR to assist in the phases of bridge inspection. AR helped in visualizing all needed data (*21*). AR has been shown to offer value for underground contexts where buried elements cannot otherwise be seen. For example, early AR researchers developed systems to display buried utility networks for above-ground users to see (*22*). A proposed AR method for pipe map projection can augment road surfaces with subsurface utility pipes, offering an improved level of accuracy and a stable alternative to using pipe maps on site (*23*). Additionally, other studies explored AR for mapping underground utilities using a mobile device by developing an integrated AR-GIS for scanning and capturing underground utilities (*24*). Researchers also investigated AR for visualization to generate a mixed view of the real world and overlaid virtual simulation objects in a construction environment by creating an AR-platform combining a hands-free video camera, GPS, tracker, head-mounted display, and a laptop computer (*25,26*). In addition, other researchers experimented with visualization of AR for construction site monitoring and documentation by proposing a system based on a 3D reconstruction of captured aerial images related to the physical environment (*27*). AR communication was also explored by researchers. Analysts studied a stationary display to facilitate the discussion process and communication between all parties by enhancing visualization (*28*). Other researchers explored AR for communication by creating a technique that enables collaboration between 2D drawings generated by CAD software and the actual physical environment. This technique allowed better communication between the designer and the builder by displaying the designed construction intent in its real context, a more accurate scheduling, bidding, and a full understanding of the whole project process (*29*). Using AR technology for communication also contributed to avoiding execution errors during all stages of a construction project (*30*).

While previous studies explored the use of AR as a new technology and its impact on the industry, many researchers consistently mentioned that their work is limited if not tested in a real environment. Cote et al. (*31*) conducted a pilot study on the use of AR in interpreting 2D drawings and concluded that investigating the development factors of the 3D perception in a construction context would be more valuable. Also, Chalhoub and Ayer (*16*), in their study exploring the use of MR for design information delivery, assembly of prefabrication electrical conduit, and interpreting of 2D drawing, considered that a controlled environment is one of the limitations that may affect the use of AR, mentioning that the performance of the user is affected by site conditions. Likewise, Shin and Dunston (*32*) mentioned in their research that the studied tracking system was a lab-based experience and was not evaluated on construction job sites, thus encouraging the need for future studies. Similarly, Wang (*33*) suggested that the "real environment surroundings" is a critical issue in AR systems and stated the necessity of studying AR structure in a real-world context. The transfer of AR systems from a controlled environment to a real construction project application will increase the flexibility and tracking of the technology, leading to real improvements in the performance and productivity of AR systems (*34*).

Published literature clearly illustrates the opportunities for AR to offer benefits for construction (i.e., safety, inspection, mapping, visualization, communication). However, the literature on how AR can be used to foster effective communication between individuals on-site and those off-site, particularly in an uncontrolled real-life construction environment, is less clear. Researchers have explored AR and other related visualization modes for remote communication but have generally tested these devices in controlled settings or required extensive user training (*35)*. This paper aims to fill this gap by building on the literature that explores controlled settings, using and testing AR on active construction sites, and identifying critical factors in these real-life settings.

3.5 Research Methodology

In order to determine factors that could impact the success of AR calls on highway construction projects, the authors implemented a research method that would elicit behavior and perception-based data, as illustrated in Figure 1. The authors first defined a workflow and prepared the participants for using AR for communication on actual project sites explained in the "AR Application: Introduction and Training" section. Subsequently, the authors recorded AR calls and conducted follow-up interviews with participants, explained in the "Data Collection' section. Finally, the collected data was analyzed to define the factors that were found to impact communication in the "Data Analysis" section. The following sections detail the steps followed in each of these major research phases.

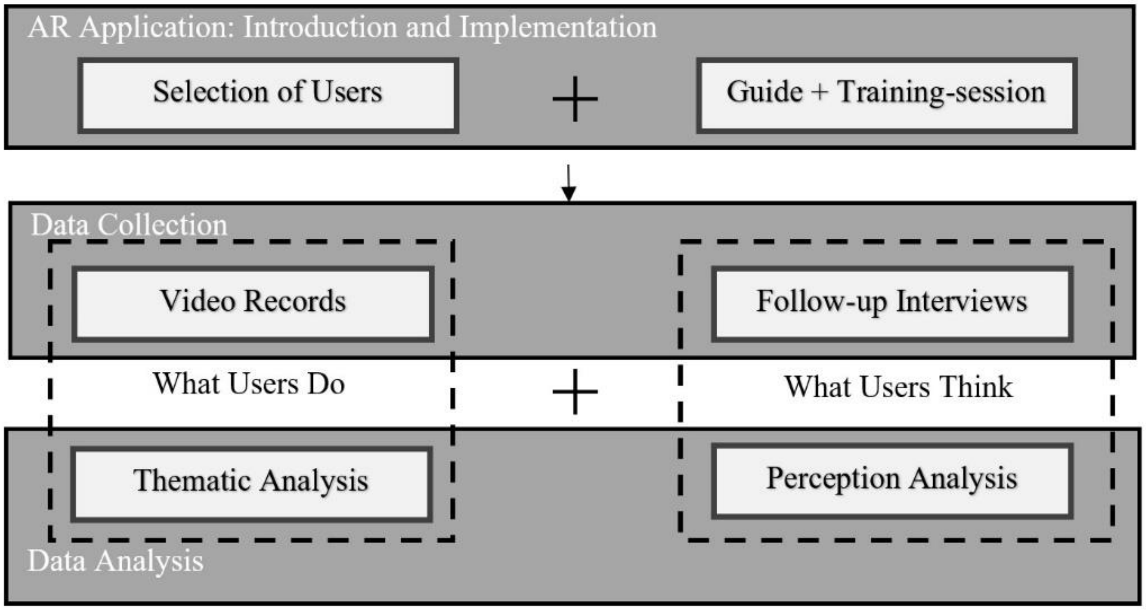


Figure 5: Research Methodology

3.5.1 Application: Introduction and Training

The authors chose to study AR communication through the use of commercially available AR software and hardware. The observations are based on AR technology that is likely to be available for use by other practitioners. More specifically, the authors elected to use "*Microsoft Teams*" and "*Microsoft Dynamics 365 Remote Assist*" to support AR communication between on- and off-site participants. The off-site participant interfaced with these tools using a standard laptop, while the on-site participant employed a Trimble *XR10*, based on Microsoft's *HoloLens-2* head-mounted display. At the time of this research's data collection, these tools represented some of the most common and robust commercially available AR tools for testing, making them ideal choices for exploring communication in uncontrolled construction sites.

Eight practitioners were identified as participants for this longitudinal study (*36),* with five working off-site and three working on-site on three different bridge projects. A longitudinal study is defined as repeated observations of the same variables enabling the authors to develop a rich understanding of users' behavior over time (36). It is important to understand how the behavior and the perception of the users toward the AR application over time can help in exploring not only the factors influencing the application but also how the users might overcome some of the challenges. A small number of users helped the authors focus not only on the factors based on the site conditions and the technology, but also on the people and process related factors. When issues emerged, AR calls would enable the participants to discuss the issue and use AR annotations to support their communication. The participants allowed the researchers to observe and record these calls for subsequent analyses. After gaining experience using AR for several calls, the authors interviewed the participants to gauge their perceptions about AR experience to help understand the behaviors observed during the recorded calls. During all scenarios, the same users were always selected to perform the call.

The next step was to prepare an "instructional user guide" for the selected users (APPENDIX A). A pre-training session was held between one of the authors and the users to become more familiar with the software and hardware in use. The three projects' activities include the: construction of additional ramps; reconfiguration of existing streets; and provision of road aesthetic enhancements.

3.5.2 Data Collection

After the participants were instructed on how to use the selected AR technologies, they identified instances that arose on their project where they believed AR calls could offer value. The on-site practitioner used a Trimble *XR10* supported by "*Microsoft Dynamics 365 Remote Assist*", while the off-site practitioner joined calls through the use of "*Microsoft Teams*". As previously noted, the participants invited a researcher to join the calls for data collection. The researcher is present during the call as a third party, for observatory and recording purposes only; the researcher does not intervene or interact with the callers. The recorded live videos document the whole communication process between both the on-site and the off-site callers. All forms of interaction between the two users are recorded. Interaction forms include verbal communication, gestures, and any documents or drawings exchange. This process is stopped after a diminishing number of new information is revealed in successive recordings, indicating a level where data saturation has been reached based on metric of ≤5% (*40*). These calls were recorded for subsequent analysis.

After testing the use of AR on real construction sites, follow-up semi-structured interviews were conducted with the practitioners to obtain an understanding of their perceptions. Some observations are externally visible and do not require confirmation from users. For others, related to their perceptions, this data helped to elucidate factors that might not have been able to be determined from video recordings alone. Interviews were conducted during an online meeting between the researcher and the participants. Meetings were recorded with the approval of both users and the university's institutional review board. The questions are divided into five main sections:

- Questions related to any previous experience or knowledge concerning AR.
- Questions related to their use of AR.
- Questions related to their utilization of *HoloLens*.
- A section for human subjects to state and categorize (Technology, people, process, and environment) the factors based on their perception.
- Open discussion.

3.5.3 Data Analysis

The video recordings provided observational data analyzed using thematic analysis, which allows for revealing important codes, repetitive and distinguished patterns (*37*). A code is a short sentence or summary attribute that symbolically represents data or information generated by the researcher (*38*). The theme is a sequence of words that present an interpretation of many similar codes or patterns (*39*). The authors followed this procedure to decode each video:

1) Transcribing the discourse between the two users manually without any software:

As a first step in analyzing the data, the authors observed the videos, and transcribed the recordings into a written discourse. Viewing, typing, reviewing, reading, and rewinding enabled the authors to familiarize themselves with the data. Therefore, while reading the transcribed document, the authors kept a record of keywords and some notes on the document itself. This process allowed the authors to identify patterns present in the data, keeping in mind the purpose of the study and its objectives. After getting familiarized with the raw data, the authors moved to the next step of thematic analysis, which consists of generating codes.

2) Generating the codes from the conversation (i.e., first order):

Codes are created after regrouping data elements based on repeated patterns and similarities in content. After transcribing the videos, each individual discourse was separated to divide the behavior and the codes generated from each practitioner, thus each speech was stored separately. The coding of the video record was not analyzed based only on the speech and the verbal discourse of the users, Gestures and movements of the person are also taken into consideration as well as the typed chat in the chat box. For example: moving around the site is not mentioned by any of the users; it is only observed by the authors. So, this kind of movement is coded based on visual, rather than verbal interaction. The authors distinguished the codes by source spoken, visual and written codes.

3) Regrouping the similar codes into themes (i.e., second order):

This next process constitutes the core task of the analysis. It involves identification of sub-themes, differentiation of themes that seem contradictory, and grouping of themes, which is the process of linking the codes under the same category. For example: the use of pen to annotate, the use of arrow to point on a subject, and sharing a document are all codes regrouped under the same theme: virtual aid.

4) Reviewing the data; ensuring overlapping and repetition of codes:

In this phase, the authors compared the generated themes from the video record to the perceptions of the users based on the follow-up interviews performed with the participants after their use of AR in real site conditions. This comparison will inform theme validation since the authors compared the naming of the themes with each other supported by this knowledge and the nomenclature of on-site and off-site users.

The themes identified will be referred to as "Factors" generated after decoding each video recorded. Factors affecting AR application on active construction projects are deduced from the regrouping of similar codes. As discussed in Guest et al. (*40*), the data collection stopped after a shrinking amount of new information was revealed in successive recordings, indicating a level where data saturation has been reached based on a metric of $\leq 5\%$.

To provide usable findings, the researchers organized the observed factors into categories related to technology, people, process, and environment, as discussed in Wu et al. (*41*). Using the same process of regrouping similar patterns. The authors used the following definitions to determine which observations would be categorized under these factors:

- Technology factors are related to the equipment used, its operation, and its functioning.
- People factors are related to users' behavior, performance, and actions.
- Process factors are related to the procedural steps followed during the call.
- Environment factors are related to time, weather, and location.

Given the uncontrolled nature of the environment for AR use in this study, some observations did not clearly relate to only one category. In order to avoid subjective interpretation, the authors organized observed factors into all plausible factors based on the evidence they collected. In other words, for some observations, multiple strategies could be pursued by subsequent researchers or practitioners to avoid the benefits or challenges observed in this work. For example, if some of the AR technical features that the software offers (i.e., annotations) is necessary for understanding the site situation and is based on the user choice (i.e., pen or arrow), then the factor related to the use of annotation would fall into three categories: technology-people-process.

These interviews offer the participants the opportunity to express their perceptions about AR and elicit factors affecting the application of this technology. Interview analysis is conducted using the same analysis method of the video recording (i.e., thematic analysis) using semantic themes (*42*). Braun and Clarke (*43*) defined semantic themes as data reflecting the explicit or surface meanings of information without interpretation beyond what the users have said.

The generated codes (i.e., observations from video and interview analysis) were listed based on the decoding of the video recordings and the follow-up interviews with the users. Then, codes were grouped into themes (i.e., factors) that influenced AR performance. Finally, these factors were organized into categories to define the underlying context that led to the observations.

3.6 Results And Discussion

Sixteen AR video calls were recorded. Table 1 shows the characteristics of each video call, the purpose, the time, the date, the duration, and the number of new codes generated in each call. All the videos were recorded on different days and times. At the end of video V6 the resulting sum of total codes found was 44. After eight more videos, only one new code was revealed. Dividing the number of codes found in videos V7 till V14 (i.e., one) by the number of codes identified by the end of prior videos (i.e., 44), the quotient reveals 2.27% new information. During two more videos (V15 and V16) only one new code was revealed reflecting 2.22% of new information. At that point, the proportion of new codes was well below the study's implemented 5% saturation threshold for the last two rounds of new video recordings. Reaching saturation is the point where data collection stops and is the basis for the sample size for this work (*40*).

Table 2: Video Characteristics

Video	Purpose	Time	Date	Duration (Minutes)	New codes identified
V1	First testing call	10:13am	02/17/2021	20:04	24
V2	Steel rebar around vent	12:30pm	02/26/2021	7:22	10
V3	Stress head location around steel rebar	9:30 am	03/02/2021	3:03	5
V4	Stress head location around steel rebar	10:59 am	03/02/2021	5:44	3
V5	Steel plates holes drill	10:09am	03/03/2021	7:47	1
V6	Concrete pouring plan	10:17pm	04/03/2021	8:01	1
V7	Test call	12:08pm	08/17/2021	9:00	0
V8	Road base material laying	07:30am	08/18/2021	21:47	0
V9	MEP road items execution follow-up	07:37am	08/23/2021	16:50	0
V10	Concrete walls patching	08:16am	08/31/2021	25:16	1
V11	Slabs steel bars coring inspection	07:53am	09/08/2021	23:58	0
V12	Follow-up	01:05pm	09/17/2021	02:23	0
V13	Side-way concrete edge inspection	07:36am	09/22/2021	15:35	0
V14	Wall concrete pouring	07:43am	10/06/2021	12:38	0
V15	Testing call, sidewalk	12:30pm	05/27/2022	58:39	0
V16	Testing call, road inspection	12:00pm	06/22/2022	21:56	1

On-site practitioners did not have first-hand experience with AR before. During this research, they acquired more than 120 minutes of first-hand use exposure to AR on site. On-site participants used the provided Trimble XR-10 in order to view and generate AR-based annotations to support communication with off-site personnel. Their manipulation was based on hand gestures and voice commands. All on-site users are engineering technicians, and both have more than 15 years of experience in infrastructure projects. The off-site users also had limited experience with AR, but they expressed their willingness to implement this technology. All off-site users are resident engineers with more than 25 years of experience in construction. After participating in several AR calls, all participants reported additional perceptions of AR through follow-up interviews.

3.6.1 On-Site Practitioner Perception

Influencing their perception, the users are confident of the usability of AR and the willingness of other professionals to adopt this technology, especially when remote work is needed. They described AR application as a "moderately efficient communication method" in supporting decision-making and solving issues on project sites. Challenges related to the use of AR based on their perception include:

1. The headphones attached to the device are uncomfortable, even when many alternative positions are attempted.
2. The combination of the hard hat with the device is heavy on the head and can result in headaches upon prolonged use. Planning the duration of the call could help in reducing this issue.
3. The internet connection can be a problem. Without having a good coverage signal, the connection would be slower. Thus, interruptions may occur during the call, especially in rural and remote areas.
4. When walking around noisy and heavy machinery, it can become hard to clearly hear the ongoing discussion.
5. Similarly, when the device was used in broad daylight, annotations were nearly impossible to see. However, when the participants used the new tinted films provided by the researchers, they were able to successfully conduct AR calls.
6. For battery and headphone chargers, the user should always remember to fully charge the battery to avoid call interruption due to battery loss.
7. Virtual manipulation and the use of the interface are unusual and difficult at the beginning but become easier with repetition.
8. Opening files or drawings during a call takes time if the file is too large.

After experiencing AR on actual site conditions, the users show openness to AR despite reporting challenges with the manipulation. They believe that it becomes easier with practice. This finding would not have been possible without the longitudinal research method that was employed for this study. The on-site users believe that AR application offers great opportunities in communication, specifically listing the following benefits:

1. Communicate with people in their offices.
2. Work remotely without wasting time driving to and from sites.
3. 3D visualization.
4. Instant drawing, documents, and annotation exchange.
5. Live overlapping augmented systems.
6. Hands-free.

3.6.2 Off-Site Practitioner Perception

The off-site practitioners described the application as an efficient communication tool supporting good decision-making. The challenging factors that they encountered are as follows:

1. The wind sound affects the clarity of the user's speech.
2. As discussed earlier, the internet connection can be a problem; without having a dedicated Wi-Fi device, the connection would be slower thus, interruptions may occur.
3. The person that actually wears the device should be experienced in manipulating the interface and performing hand gestures.
4. Annotation colors can sometimes be unclear; the choice of color must be chosen strategically with the background.

The off-site users reported that the manipulation of AR during the call was relatively easy and can improve with practice. They listed the following benefits of AR application:

1. Working remotely and saving time and money associated with traveling to and from remote sites.
2. AR can also work at night.
3. The off-site user's calling process was easy.
4. AR virtual aid features, such as annotations and the possibility of exchanging documents, support the communication process.
5. Detect and predict mistakes, also provide instant solutions by having a clear vision shared by the on-site user.

Request for information (RFI) processes experienced on most construction projects can take weeks to resolve. Users believe that AR can help solve these issues, thus saving time needed submitting RFIs and waiting for responses. They reported that AR promotes real-time collaboration enhancing good decision-making.

3.6.3 Classification of Factors

The codes uncovered during interviews with the users confirm those initially decoded by the authors during the study of the recorded videos. By categorizing the codes found via direct observations, the users were able to validate the factors while conducting the interviews with the users. The codes revealed from the data collection helped the authors classify the factors into the categories of technology, people, process, and environment related, as shown in Fig. 2. As discussed earlier, some factors could be associated with multiple categories at the same time. The factors identified are displayed in Table 2 and will be later discussed in more detail.

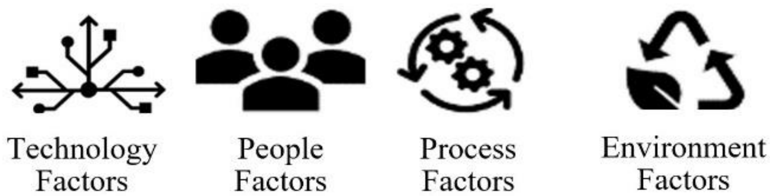


Figure 6: Table Legend

Table 3: Classification of Codes and Factors

Codes Generated	Category				Factors	Impact	
	(Technology)	(People)	(Process)	(Environment)		Benefit	Challenge
The use of hand gesture virtual manipulation	x	x			Virtual Manipulation		x
Repeat hand gestures to move the interface	x	x					
Repeat in finger-clicking gesture	x	x					
Moving with the virtual interface		x					
Instant drawing exchange	x	x	x		Visual Aid	x	
Use of arrow to annotate	x	x	x				
Use of pen to annotate	x	x	x				
Desire for extra visuals, drawings			x				
Request for visual clarification			x				
Desire to measure		x					
Expressing that the annotations are not clear enough	x						x
Time to insert a file	x						
Description of the situation with vision			x		Share Action Plan	x	
Provide instruction			x				
Give Solution			x				
Point to objects with a finger	x				Hands-free	x	
Do other activities	x						

Codes Generated	Category				Factors	Impact	
						Benefit	Challenge
Moving objects around the site	x						
Agreeing into solution / decision		x	x		Decision-Making	x	
Confirmation of understanding		x	x				
Report the ability to hear each other	x	x			Site Interaction / Site Involvement	x	
Report the ability to see the person talking to	x	x					
Showing satisfaction about the solution		x					
+4 person call configuration	x		x				
Expressing the situation as doing inspection	x	x			Working Remotely	x	
Expressing gratitude when remotely solving a problem	x	x					
Inviting all attendees to the meeting prior to the scheduled time	x						
Appreciation of recording		x			Repetition and Back-up Information	x	
Recording the call	x		x				
Moving around the site	x	x			Locomotion	x	
Moving with the virtual interface	x	x					
Moving objects around the site	x	x					
Testing call			x		Performing Different Types of Jobs	x	
Sharing live vision of concrete pouring activity			x				
Expressing the situation as doing the inspection			x				
Expressing concerns with the device weight	x	x	x		Device Discomfort		x
Expressing issues with the comfort of using the headphones	x	x	x				
Relocation due to near background noise				x	Background Noise		x

Codes Generated	**Category**				**Factors**	**Impact**	
						**Benefit**	**Challenge**
Repetition of statements due to wind sound				x			
Making calls at night				x	Lighting Conditions	x	
Use of tinted films (i.e., shading device)	x	x					
Expressing concerns due to sun glare	x			x			x
Bluetooth disconnection	x				Disconnection in Hardware Physical and Features Components		x
Battery disconnection	x						
Internet disconnection				x			

Virtual manipulation is a factor related directly to the hardware, revealed through the observation of four codes: "The use of hand gestures"; "repetition of finger movement for clicking"; "repetition of hand gesture"; and "moving with the virtual interface". These codes represent features offered by the technology but controlled by the users' actions, thus they are technology- and people-related. Noting the ability of the users to adapt to the virtual manipulation with repetition and practice, the fourth code: "moving with the virtual interface", is only people-related because it shows the user's success in moving and adapting to the virtual features after many repetitions. Based on the observation and the interviews conducted with the users, this factor poses a challenge for the on-site practitioner. Manipulation difficulties is shown at early stages of AR application, with each time the practitioners used the application, they were practicing and getting familiar with the gesture and the movement. Related codes are present during V1 and V2. But after multiple exposure and repetition of the hand gestures, the users expressed adaptation and improvement which lead him to overcome this problem. This illustrates the need to have some previous practice sessions prior to direct application of AR in real live construction sites.

Visual Aid is another factor discovered offered by the software in use, representing virtual features like annotations and technical features like document exchange. In general, these visual aids are beneficial to the application, except when practitioners have lack of knowledge and strategies to the use of these features. These challenges are expressed by the users and noted in the observations and are technology-related because they are considered to be variables related to the equipment and its functioning.

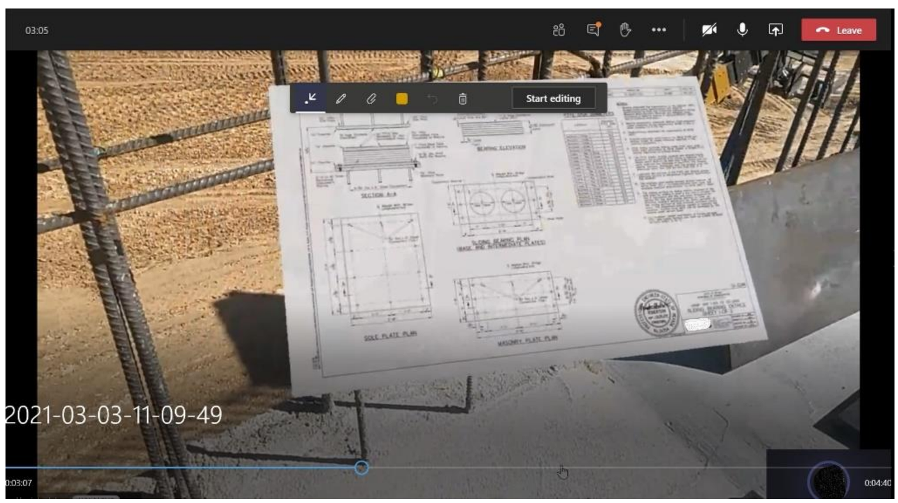


Figure 7: Drawing Exchange Using AR.

Based on the observations, some problems raised at the first stages of the AR application but eased with extra use over a period of time. In V1 and V2 the users sharing large files and annotating proved to be problematic due to the long time needed to be opened and the chosen annotation color. However, users show adaptation with the AR application features during the next videos: to reduce the size of the shared files prior to the call and to change the color of the used annotation. This highlights the importance of preparation prior to conducting an AR call. Meaning that for some of certain types of issues that arose during early AR calls, simple procedural preparation changes can actually mitigate these problems. Fig.3 shows a virtual drawing exchange opened in from of the on-site user.

Sharing an action plan is another factor defined by three codes; “description of the situation with vision”, “provide instructions” and “give a solution”. These three codes are important and practical steps to define a decision at the end of a call; thus, they are only process related. Similarly to the “Decision-making” factor which is often the ultimate result of a call between the two users, these factors are considered to be beneficial to the application of AR because they show an important characteristic of this technology, which is combining the benefits of a phone call with a live vision of the site. Reporting the ability to hear and see each other, by turning the camera on or off (choice controlled by the users), is a beneficial feature that helps the off-site user to become more involved in the site. Same as the ability to have a group call like a meeting setup, improves the interaction between all callers. Another benefit is noted to by this application is the ability to “work remotely.” This factor is related to the ability of the users to plan and schedule a virtual meeting live from the site ahead of time, instead of waiting for the call to be received from the site. Working remotely is also related to the user’s actions when: expressing what they are doing remotely; executing; and showing positive gratitude for solving the problematic situation without wasting time driving to the site Fig. 3, 4. Repetition and information back-up is a factor that is defined by two codes: “appreciation of recording” and “recording the call.” While the appreciation of recording a code is a pattern related to the users (i.e. people-related), the action of recording the call is a code that is related to technology and process. The equipment offers the feature of recording the call, and by recording it and backing up the information it helps the process to attain and repeat solutions for present and future problematic situations. Locomotion is another factor related to the ability of the on-site user to move during the call, sharing different context views and not confined to one vision. Being able to do so is considered to be a benefit to the application. Locomotion is a factor that falls into both technology and people categories. In V2, V3, V4, and V5, the on-site user expressed that the purpose of the call was an inspection. And, in V6 the purpose of the call was to share the vision of an actual live concrete walls pouring. The diversity of types of AR calls illustrates beneficial ways in which AR may support communication for various site activities. This factor is process related.

Hands-free is also another beneficial factor related to the hardware in use. Trimble *XR10* is a head-mounted device that enabled our user to have free hands so they could perform other activities during the calls. Fig.4 shows how the on-site user is performing a measuring task using both his hands. This factor is technology-related, and an advantage offered only with this type of equipment. However, this type of hardware also shows a challenging factor expressed by the users: Device Discomfort. Being head-mounted, the device and the headset can feel

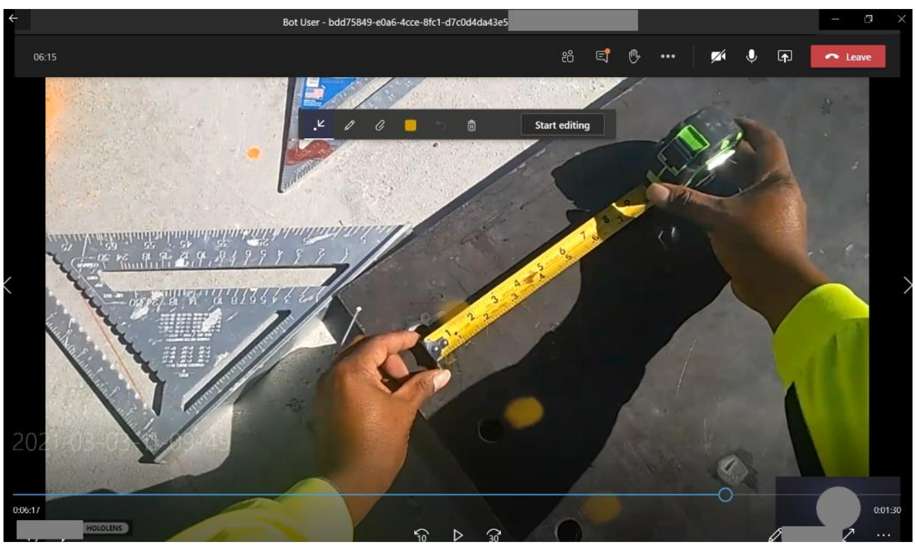


Figure 8: Handsfree Operation Allows the Used to Measure Components.

heavy and somewhat uncomfortable after a period of time. This factor is primarily technology-related since it is related to the type of device (i.e. head mounted). Second, it is considered to be people-related because it is connected to the users' behaviors and actions upon sizing the hat on their head while wearing it. Third, this factor is also process-related since it is affected by the duration of wearing the device. By simply establishing a procedural plan for the duration of the call, the users suggested that this can minimize the issue.

Background noise is a factor expressed as a challenge by the users. This challenge affects the quality of the sound transmitted, which often requires dialogue repetition, increasing confusion and delays. This factor is environment related. To overcome this challenge, the on-site user should purposefully choose where to stand during the call and attempt to distance him or herself from loud equipment. Observations show that when facing such problems related to surrounding noise, users directly adapt by simply alternating their behavior, similarly to another factor: Disconnection in hardware physical and features components. In V4, and due to an unstable internet connection, the call between the two users was lost after only five minutes and forty-four seconds. To overcome this issue, the on-site user showed adaptation by planning the duration of the call, establishing a good internet connection using a portable Wi-Fi device, along with ensuring enough battery life for both the device and the headset, to avoid any disconnection.

Lighting condition is another factor that constitutes a challenge reported by the users during the interviews. This challenge was also recognized during the internal testing of the researchers at the beginning of this study. Lighting condition includes three codes:

"make calls at night", "expressing concerns due to sun glare", and "use of tinted films" (i.e. shading device). The on-site user expressed satisfaction about the use of AR during the night, such as during recording V6. However, for findings related to daylight, which is a commonly reported challenge for outdoor AR use, the users expressed concerns in the clarity of the vision due to sun glare. The authors introduced low-cost solutions using tinted films, which were successful at mitigating the limitations posted by harsh sunlight. While this does not negate challenges posed by extreme sunlight, it offers a simple near-term solution to address this challenge. The use at night, Fig 5, is an environment-related code, whereas sun glare is related to both environment and technology because the equipment is highly affected by the glare. The use of a tinted film is technology-people-related because it is based on the user action and positioning versus sun glare and direction.

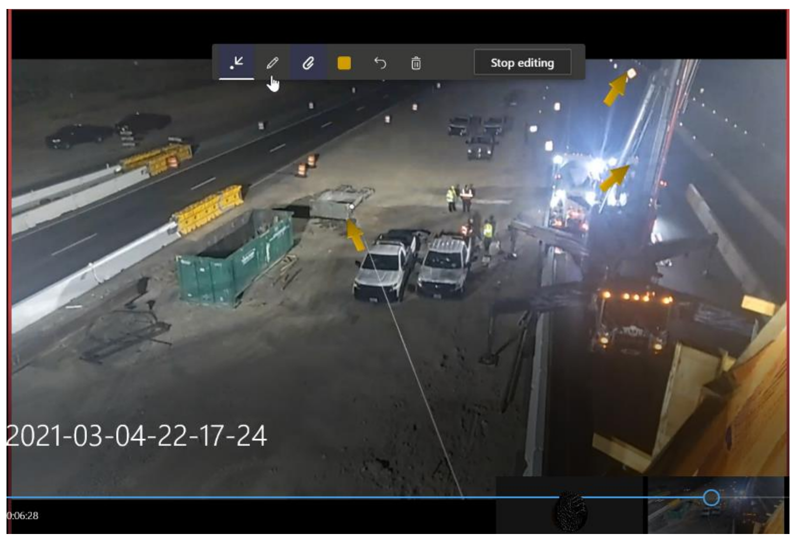


Figure 9: Call Conducted at Night, With Yellow Annotations (Arrows)

Some previous studies documented beneficial and non-beneficial aspects of AR applications, showing factors affecting the implementation of AR. This paragraph document prior stated factors in the literature. Similar to the findings of this study, Wu et al. reported that AR enhances on-site visualization even with inexperienced users *(41)*. Also, previous studies mentioned similar negative factors such as the noise, the weather, the sun glare, and the heat (*16, 17, 41, 44, 45, 46)*. Additionally, Chalhoub and Ayer agreed that the hat is heavy, and further investigation on lighter and smaller hats is needed (*16*). The use of AR in broad daylight proved to be challenging with sun glare, unless additional tinted filters were used. Additionally, the users initially struggled with the use of gestures for AR user interface movement and control. Moreover, Cheng et al. mentioned the same factors in addition to: having hands-free while using AR devices, improving communication, increasing involvement in site problems, enhancing the interaction between people on-site and off-site, and using AR in different site scenarios as inspections and equipment operations (*44*). Unlike the factors mentioned in the literature, factors revealed in this paper were actually observed during AR implementation on active highway construction sites. Many factors cited in previous research were presumed or deduced by the researcher, based on studies in controlled environments.

By organizing these factors into categories, the findings inform practitioners and future researchers about opportunities and challenges associated with AR application on active construction sites. Some of the challenges may be solved through simple technological innovations, such as tinted films, to overcome the problems associated with lighting conditions. Furthermore, other challenges related to the environment were overcome by simply adapting to them. Taking the example of the background noise factor, the on-site user simply changed his location to avoid the noise affecting the clarity of the transmitted sound. Other challenges can be solved by instituting a standard process. For instance, sharing smaller size documents to avoid wasting time, choosing an appropriate color of the annotations to avoid unclear annotations, and so on. Also, other challenges could be resolved by training and repetition; offering training sessions or workshops for users can help avoid the problems related to the virtual manipulation and functioning of the AR device. Users showed and expressed that they could adapt to the virtual hand gesture and the manipulation of the device by repetition.

3.7 Conclusions

This paper identified factors that impact AR communication between on-site and off-site practitioners. The factors were generated from observing the performance of users in uncontrolled construction environments, as well as follow-up interviews asking about their perceptions. Forty-six codes were extracted, revealing 14 key factors. The authors were able to classify the identified factors into categories spanning technology, people, process, and environment. By documenting these factors, this paper identifies ways in which AR technologies may, and may not, immediately support site-based communication for ongoing construction applications. Some factors offered by this technology represent benefits; others pose challenges. AR communication tools make the communication process, sharing data, and recording of information more efficient and useful during construction and post-construction. The challenges related to AR application are associated with the type of tool used, its features, and the surroundings. Some of these factors were addressed by simple solutions suggested by the users and the authors, such as tinted films; others were overcome by the users' repetition and practice.

These challenges constitute great foundational material for future studies, which may motivate practitioners and researchers alike to tackle the identified challenges and define robust solutions Building on the environment-related drawbacks like internet connection in remote areas, sun glare in the summer, and construction site noise, future research could focus on finding advanced technical solutions to these drawbacks. Building on other types of challenges that were identified in this paper, future research could focus on training workshops that allow users to practice in uncontrolled real-life environments like the work presented in this paper and creating an instructional framework to help users choose the best device supporting AR application depending on particular scenarios and conditions they are facing.

It is important to note that the authors do not claim to have identified an all-encompassing and comprehensive list of the factors. The authors conducted this exploratory work using a longitudinal study which aims to observe repeated behaviors and actions of users over a period of time using AR technology in uncontrolled environments. These observations allowed the authors to not only extract the factors that are affecting the use of this technology, but also to observe how issues related to these factors can be overcome. One possible limitation of this study is that there may be other factors that could emerge through more testing and use of AR in an infinite number of cases and scenarios on unique construction projects. That does not negate the importance of the key factors revealed in this study, which did in fact reach “saturation”, but it does open the door to the possibility of uncovering other benefits and challenges in the future. In fact, given the high cost of conducting larger data collection efforts on “in-progress” construction sites, it would be unwise to attempt quantitative evaluations of AR without first understanding what factors are worthy of exploration, which is exactly what this paper provides. Therefore, this work serves as a foundation on which future quantitative work may build. Another limitation is that all testing was conducted on highway projects, to ensure a focused scope. In fact, it is noteworthy to mention that many factors revealed are not affected by the type of projects or scenarios. For example, the use of hand gestures for virtual manipulation is a factor related directly to the type of device in use and not to the site conditions or type of project.

Future research can build on the findings of this exploratory study, working with engineering and construction practitioners to collect more data that extends the sample beyond DOT practitioners and also includes consultants, builders, and others. As further studies exploit the benefits and remove barriers to effective AR communication, AR may become a viable strategy to address some of ASCE's broad aims (*47*), including offsite parts transportation and workers' training preventing safety accidents.

References

1. Pheng L.S. and Hou L.S. The Economy and the Construction Industry. Construction Quality and the Economy; 2019. 21-54. DOI:10.1007/978-981-13-5847-0_2

2. Gamil Y. and Abdul Rahman I. Identification of Causes and Effects of Poor Communication in Construction Industry: A Theoretical Review. Emerging Science Journal; 2017. Vol.1, no.4. DOI:10.28991/ijse-01121

3. Kazi, A.S. Knowledge management in the construction industry: A socio-technical perspective. IGI Global. Technology & Engineering; 2005. p.384. DOI: 10.4018/978-1-59140-360-9

4. Emmitt S. and Gorse C. Communication in Construction Teams. Taylor&Francis e-Library; 2006. DOI:10.4324/9780203018798

5. Goh, K C Goh, H H, Toh, S H and Peniel A. Enhancing communication in construction industry through BIM. Proceedings of the 11th International Conference on Innovation & Management; 2014. PP (313-324)

6. Dainty A., Moore D. and Murray M. Communication in construction, theory and practice. Taylor&Francis, London; 2006. DOI:10.4324/9780203358641

7. Sperber D. and Wilson D. Communication and Cognition. Blackwell's, Oxford; 1986

8. Cheng W. L. E., Li H., et al. Network communication in the construction industry. Corporate Communications: An International Journal; 2001. Vol.6, nb.2.61-70. ISSN1356-3289

9. Minooei F., et al. Managing Public Communication Strategies in Accelerated Highway Construction Projects. Journal Of The Transportation Research Board; 2018. https://doi.org/10.1177/0361198118759943

10. Milgram, P., and Kishino, F. Taxonomy of mixed reality visual displays. IEICE Transactions on Information and Systems; 1994. 1321–1329

11. Azuma, R. T. A. Survey of Augmented Reality. Presence: Teleoperators and 155 Virtual Environments; 1997

12. Berner A. Augmented Reality The Past, The Present and The Future. Interaction Design Foundation (IxDF); 2020. interaction-design.org

13. Broll W., Lindt, I. et al. ARTHUR: A collaborative augmented environment for architectural design and urban planning. Journal of Virtual Reality and Broadcasting; 2004. Vol.1, no.1.

14. Dunston, P., Wang, X., Billinghurst, M., and Hampson, B. Mixed Reality Benefits for Design Perception. Washington, DC, USA; 2003

15. Wang, X., and Dunston, P. S. User perspectives on mixed reality tabletop visualization for face-to-face collaborative design review. Automation in Construction; 2008. 17(4),399–412

16. Chalhoub, J., and Ayer, S. K. Using Mixed Reality for electrical construction design communication. Automation in Construction; 2018. 86,1–10

17. Chalhoub, J., and Ayer, S. K. Exploring the performance of an augmented reality application for construction layout tasks. Multimedia tools and applications; 2019. Vol.78(24). https://doi.org/10.1007/s11042-019-08063-5

18. Kim, K., Kim, H., and Kim, H. Image-based construction hazard avoidance system using augmented reality in wearable device. Automation in Construction; 2017. 83,390–403

19. Park C-S. and Kim H-J. A framework for construction safety management and visualization system. Automation in Construction*; 2013.* 33,95–103

20. Moreu, F., Lippitt, C., Maharjan, D., Aguero, M., and Yuan, X. Augmented Reality Enhancing the Inspections of Transportation Infrastructure: Research, Education, and Industry Implementation; 2019

21. Salamak M. and Januszka M. BIM Models and Augmented Reality for Concrete Bridge Inspections. 11th CCC Congress HAINBURG; 2015. DOI:10.13140/RG.2.1.5161.0329

22. Roberts, D. G. W., Evans, A., Dodson, A. H., Cooper, S., and Hollands, D. R. The Use of Augmented Reality, GPS and INS for Subsurface Data Visualization; 2002

23. Cote, S., and Mercier, A. Augmentation of Road Surfaces with Subsurface Utility Model Projections. IEEE Conference on Virtual Reality and 3D User Interfaces (VR*)*; 2018. Reutlingen,535–536.

24. Fenais, A., Ariaratnam, S. T., Ayer, S. K., and Smilovsky, N. Integrating Geographic Information Systems and Augmented Reality for Mapping Underground Utilities. Infrastructures; 2019. 4(4),60.

25. Behzadan, A. H., and Kamat, V. R. Visualization of Construction Graphics in Outdoor Augmented Reality. Proceedings of the Winter Simulation Conference, IEEE, Orlando, FL. USA; 2005. 1914-1920.

26. Behzadan, A. H., and Kamat, V. R. Simulation and visualization of traffic operations in Augmented Reality for improved planning and design of road construction projects. Winter Simulation Conference, IEEE, Miami, FL, USA; 2008. 2447–2454.

27. Zollmann, S., Hoppe, C., Kluckner, S., Poglitsch, C., Bischof, H., and Reitmayr, G. Augmented reality for construction site monitoring and documentation. Proceedings of the IEEE; 2014. 102(2), 137–154.

28. Lin, T.-H., Liu, C.-H., Tsai, M.-H., and Kang, S.-C. Using Augmented Reality in a Multiscreen Environment for Construction Discussion. Journal of Computing in Civil Engineering; 2015. 29(6),04014088.

29. Côté, S., Trudel P., Desbiens M-A., Giguere M., and Snyde R. Live Mobile Panoramic High Accuracy Augmented Reality for Engineering and Construction. Proceedings of the 13th International Conference on Construction Applications of Virtual Reality; 2013. 30-31, London, UK.2

30. Ganah A., Anumba C. J., Bouchlaghem N. M. Computer Visualisation as a Communication Tool in the Construction Industry. Proceedings Fifth International Conference on Information Visualization; 2001. DOI**:**10.1109/IV.2001.942129

31. Côté, S., Beauvais M., Girard-Vallée A., and Snyde R. A Live Augmented Reality Tool for Facilitating Interpretation of 2D Construction Drawings. Springer International Publishing Switzerland; 2014. LNCS 8853. DOI:10.1007/978-3-319-13969-2_32

32. Shin, D. H., and Dunston, P. S. Evaluation of Augmented Reality in steel column inspection. Automation in Construction; 2009. 18(2),118–129.

33. Wang X. Augmented Reality in Architecture and Design: Potentials and Challenges for Application. SAGE Journal; 2009. https://doi.org/10.1260/147807709788921985

34. Wang, X., and Dunston, P. S. Tangible mixed reality for remote design review: a study understanding user perception and acceptance. Visualization in Engineering; 2013. 1:8

35. Harikrishnan A., ·Abdallah A.S., Ayer S.K., El Asmar M., PingboTang P. Feasibility of augmented reality technology for communication in the construction industry. Advanced Engineering Informatics, ELSEVIER; 2021. https://doi.org/10.1016/j.aei.2021.101363

36. Lee, S. and Yu J. Longitudinal Study on Construction Organization's BIM Acceptance. Applied sciences; 2020. doi:10.3390/app10155358

37. Clarke, V. and Braun, V. Teaching thematic analysis: Overcoming challenges and developing strategies for effective learning. The Psychologist; 2013. *26*(2),120-123.

38. Vogt W. P., Gardner C.D., Haeffele L.M. and Vogt E. R. Selecting the Right Analyses for Your Data: Quantitative, Qualitative, and Mixed Methods. Guilford Publications -Social Science; 2014

39. Labra O., Castro C., Wright R. and Chamblas I. Thematic Analysis in Social Work: A Case Study. Cutting Edge Issues and Critical Reflections, Bala Raju Nikku, IntechOpen; 2019. DOI:10.5772/intechopen.89464.

40. Guest G., Namey E., and Chen M. A simple method to assess and report thematic saturation in qualitative research. PLoS ONE; 2020. https://doi.org/10.1371/journal.pone.0232076

41. Wu W., Sandoval A., Gunji V., Ayer S., London J., Perry L., Patil K., and Smith K. Comparing Traditional and Mixed Reality-Facilitated Apprenticeship Learning in a Wood-Frame Construction Lab. ASCE; 2021. DOI:10.1061/(ASCE)CO.1943-7862.0001945

42. Moira Maguire & Brid Delahunt. Doing a Thematic Analysis: A Practical, Step-by-Step
Guide for Learning and Teaching Scholars. All Ireland Journal of Teaching and Learning in Higher Education; 2017. http://ojs.aishe.org/index.php/aishe-j/article/view/335

43. Braun, V. & Clarke, V. Using thematic analysis in psychology. Qualitative Research in Psychology; 2006. 3,77-101.

44. Chen C.P. J., Chen K. and Chen W. State-of-the-Art Review on Mixed Reality Applications in the AECO Industry. Journal of Construction Engineering and Management, ASCE; 2020. V146, Issue 2. DOI: 10.1061/(ASCE)CO.1943-7862.0001749

45. El Kassis R., Ayer S. K., El Asmar M., and Tang P. Defining Factors that Support or Hinder Commercially Available Augmented Reality (AR) Devices for Construction Communication. American Society of Civil Engineers, Internation Conference on Computing in Civil Engineering. i3CE. Orlando, Florida, United States; 2021. https://doi.org/10.1061/9780784483893.159

46. El Kassis R., Ayer S. K., El Asmar M., and Tang P. Augmented Reality Communication on Active Construction Sites: A Pilot Study Exploring Non-

Technological Factors. American Society of Civil Engineers, Construction Research Congress 2022: Computer Applications, Automation, and Data Analytics; 2021. https://doi.org/10.1061/9780784483961.126

47. ASCE American Society of Civil Engineers. Future World Vision: Infrastructure Reimagined; 2019. Future World Vision: Infrastructure Reimagined (asce.org)

CHAPTER 4

A Guiding Framework Supporting Augmented Reality Implementation for Synchronized Communication

4.1 Publication Information

The text presented in this chapter was submitted for publication to Practice Periodical on Structural Design and Construction under the title " A Guiding Framework Supporting Augmented Reality Implementation for Synchronized Communication" (El Kassis et al., 2022) and is awaiting peer feedback.

4.2 Abstract

Effective communication is essential in the construction industry to ensure coordination and collaboration among stakeholders for successful project outcomes. However, traditional communication methods often fall short in meeting industry's complex demands, often leading to delays, errors, and increased cost. This emphasizes the need for innovative communication solutions, including augmented reality (AR), to help improve communication practices in construction. By integrating virtual elements onto the real-world, AR enhances visualization, information sharing, and collaboration; these are some of the benefits of leveraging AR to ease communication challenges between project stakeholders in various locations. AR tools and applications include remote collaboration, virtual site visits, and real-time progress tracking. However, the successful adoption of AR in construction requires use-based guidance to inform users on effective AR utilization, including guidance on which tools may be feasible and beneficial in a given context. Previous studies exploring the use of AR as a

communication tool have revealed different factors affecting the efficacy of using this technology. The objective of this paper is to build on the previously reported factors affecting the efficacy of AR for communication on live construction sites to create a guiding framework for implementation of technological tools and methods supporting successful AR implementation. This framework is developed based on rounds of modified Delphi panels that comprise panelists that have previous experience in using AR for communication, and panelists without experience with AR. In capturing both user types as Delphi panelists, the authors ensure that the developed framework is practitioner-friendly and can guide effective decision-making.

4.3 Introduction

The construction industry, which significantly contributes to economic activity and national growth, relies heavily on effective communication among its various stakeholders (*1*). Traditionally, communication has been facilitated through methods such as site visits and phone calls (*2*). In the context of highway projects, efficient communication plays a crucial role in establishing trust between stakeholders and minimizing misunderstandings that often lead to the need for rework, which can cause construction delays. Traditional communication methods, like site visits and other in-person meetings, can support effective communication and build trust among stakeholders. However, these communication methods also come with inherent drawbacks. Face-to-face communication during site visits allows for a natural and immersive mode of interaction, enabling all project participants to physically explore the site and gain a comprehensive understanding of relevant constraints. However, this approach may result in stakeholders spending extended time commuting to and from remote locations. On the other hand, relying solely on phone calls and verbal exchanges, which lack visual context, can lead to misinterpretation of site details and potentially contribute to poor decision-making in certain situations. Researchers have delved into the impacts of poor communication in the construction industry and have identified negative effects, such as time and cost overruns, resulting from these communication challenges (*3*). By leveraging innovative communication technologies that combine the benefits of in-person interaction and visual representation, the construction industry can overcome some of the limitations of traditional communication methods. Such tools would enable stakeholders to have meaningful discussions while simultaneously providing a clear and comprehensive understanding of the site's characteristics. This approach aims to enhance communication efficiency, minimize errors and misunderstandings, and ultimately improve decision-making processes throughout the construction lifecycle. This underscores the critical need for effective and efficient communication in construction projects and serves as motivation to explore new communication tools that facilitate both verbal discussions and effective visualization of a site's context. One such tool, Augmented Reality (AR) supports effective communication amongst construction project stakeholders and simultaneously helps reduce travel time, alleviate traffic congestion, and decrease costs associated with the project (*4*).

Augmented reality (AR) is an emerging technology with numerous applications in the construction industry. It involves overlaying virtual objects onto the real environment, creating the illusion that both the virtual and real elements coexist simultaneously (*5*), allowing users to perceive the real world while simultaneously viewing virtual objects integrated into it (*6*). In the context of highway construction, AR can facilitate the viewing of a consistent representation of a construction site for both on-site and off-site users. This can involve the superimposition of relevant models, drawings, text, or arrow annotations onto the actual view of the space during a live conversation between the callers (*7*). Multiple studies have discussed the types of devices that are compatible with AR applications for synchronized communications (*8*, *9*, *10*). On-site users have the option of using head-mounted devices that can be equipped with an online platform, such as Microsoft Dynamics 365 Remote Assist, which enables AR calls. Alternatively, they can utilize cellphones or tablets that also have the capability to download and run similar platforms. Meanwhile, off-site users have the flexibility to utilize laptops or similar devices such as cellphones or tablets, equipped with online communication platforms like Microsoft Teams, which is widely recognized and familiar to most industry professionals (*9*).

Daio and Shih report that while there have been many studies exploring the use of AR for communication in the construction industry, most of them have focused on the challenges and opportunities of implementing AR applications (*10*). However, there is a notable gap in the literature when it comes to providing comprehensive insights into how AR effectively facilitates communication within the industry, specifically on active construction sites where many variables are uncontrolled, as opposed to in laboratory environments, where most variables are controlled. Practitioners in the field are left without clear guidance on the practical means and methods of utilizing AR for communication purposes on construction sites. The absence of concrete recommendations on selecting the appropriate technological tools and equipment further compounds the issue. As a result, there is a pressing need for more in-depth studies that address these specific aspects, offering practical advice and guidelines for practitioners seeking to leverage AR technology for effective on-site communication in the construction industry. Consequently, the objectives of this paper are to:

1. Create a decision-support framework for highway project stakeholders to use as they consider using AR on their project.

2. Understand the ways in which implementation of this framework may support decision-making about whether or not to leverage AR on their highway project.

3. Understand the ways in which implementation of this framework may support decision-making about which technological tools may be best for their project.

4.4 Background And Literature Review

Previous research has focused on exploring the use of augmented reality (AR) as a new technology, as well as its impact on various industries. These studies have investigated the utilization of AR in multiple areas, including information exchange methods (*11*), design review (*12*), construction layout tasks (*13*), construction inspections and monitoring (*14, 15*), and visualization of construction activities (*16*). These studies highlighted the significant impact of site conditions on the implementation of augmented reality (AR) in the construction industry. They emphasized the necessity of considering these conditions and their influence on AR effectiveness (*13*). Moreover, these studies suggested that conducting AR experiments and investigations in real environments would be invaluable in understanding the factors that influence 3D perception within a construction setting (*17*). Wang (18) underscored the critical importance of considering the "real environment surroundings" when designing and deploying AR systems in construction projects. Similarly, Shin and Dunston (*19*) emphasized that the adaptability and tracking capabilities of AR technology could be greatly enhanced by considering the actual on-site conditions. By incorporating real-world contexts into AR development, tangible improvements in the performance and productivity of AR systems can be achieved (*16*). The importance of conducting studies that involve augmented reality (AR) in real construction sites cannot be overstated. By conducting AR experiments and investigations in these authentic environments, researchers can gain valuable insights into the practical implementations and impacts of implementing AR technology in the construction industry. This real-world context allows for a more comprehensive understanding of the challenges, limitations, and opportunities that arise when using AR in construction projects. Furthermore, integrating real-world contexts into the development of AR systems is crucial for achieving tangible improvements in their performance and productivity. By considering the actual on-site conditions, such as the physical layout, environmental factors, and operational constraints, developers can tailor the AR technology to meet the specific needs and requirements of construction projects. Moreover, knowledge about construction site conditions enables the creation of more effective and efficient AR systems that seamlessly integrate into real construction sites. Overall, by conducting AR studies on real construction sites and emphasizing the incorporation of real-world contexts into AR development, the construction industry can unlock the full potential of AR technology. In turn, this can lead to significant advancements in performance, productivity, and overall project outcomes, ultimately benefiting the industry as a whole.

From the few papers that have explored the use of augmented reality (AR) in uncontrolled environments, researchers have reported challenges with AR virtual interface manipulation, particularly when physically moving, using a head-mounted device (*20*). Other studies have indicated that proper guidance and practice are necessary for effectively controlling the virtual interface of AR (*21, 22*). Additionally, it has been observed that the type of device used for AR applications, such as headsets or cellphones/tablets, can impact user comfort, especially during prolonged use (*23, 24, 25*). Different weather and environmental conditions can also affect the suitability of the AR device (*26*). For instance, sun brightness has been found to have a greater impact on headsets compared to cellphone or tablet-based AR (*27*). Similarly, researchers have observed differences in the field of view between various types of devices that support AR applications (*28*). Headsets, for example, offer a different field of view compared to cellphones or tablets (*9*). Furthermore, several factors have been identified that can affect the performance and suitability of tools and devices used for AR (*29, 30*). These findings underscore the importance of providing guidance to practitioners regarding the different types of devices available and their suitability for specific site conditions. Considering factors such as environmental factors and device specifications becomes crucial in facilitating the implementation of AR. By informing practitioners about these considerations, the process of integrating AR technology can be made more efficient.

Therefore, the objective of this paper is to develop a decision-support framework that highway construction project stakeholders can use to make decisions about if and how to implement AR on their project. The framework considers the specifications of different tools and devices, as well as specific construction site conditions. By utilizing this framework, users will be equipped with the necessary information to make decisions when choosing the most suitable device for effective AR implementation in synchronized communication scenarios.

4.5 Research Methodology

The Modified Delphi Panels method is an iterative consensus-building approach used to gather opinions and expertise from a group of individuals, typically experts in a specific field or topic (*31*). The authors chose to apply this method to facilitate consensus between practitioners using AR on construction sites as illustrated in Figure 1. This method allows for gathering and synthesizing user opinions on the framework structure and application. The following sections detail the steps followed in each of these major research phases.

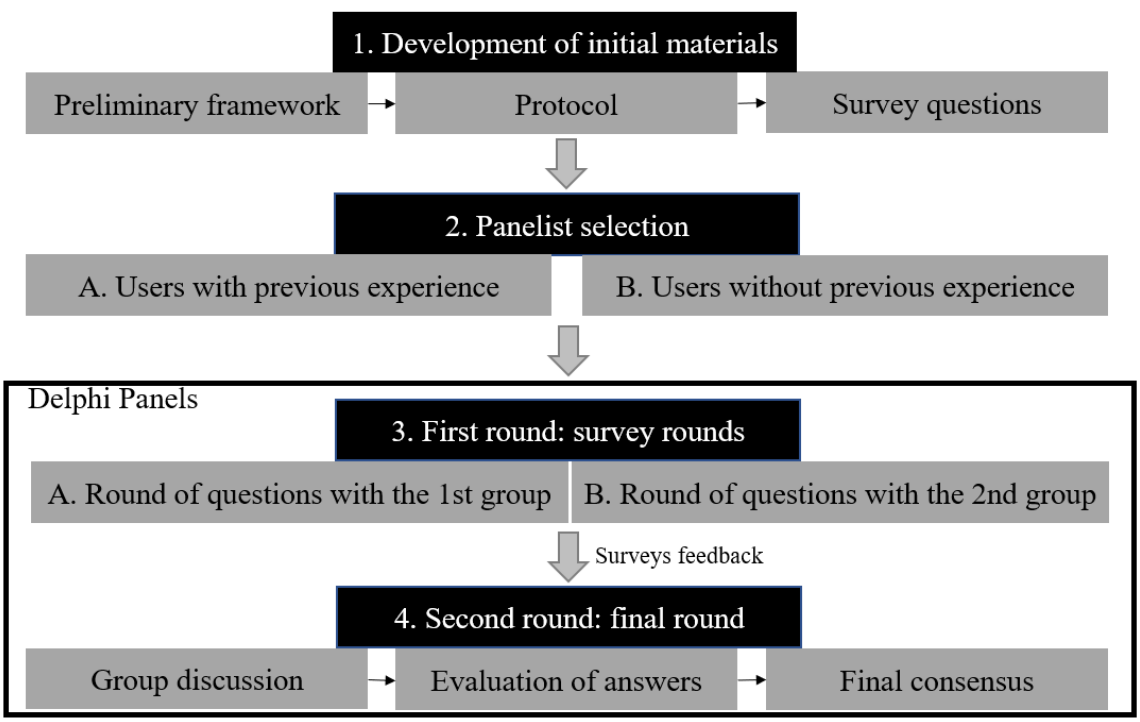


Figure 10: Research Methodology

4.5.1 Development of Initial Materials

The first step in the methodology section involved the development of initial materials that would be utilized for the Delphi panels.

First, the authors reviewed previously published papers (*8, 9)* and extracted relevant factors, i.e., those factors that impact the ability to implement AR on a construction site as well as the efficacy of this implementation). These factors are organized into a preliminary decision-support framework based on the technological tools used to implement AR as well as the contexts in which these factors were encountered, e.g., environmental factors. This decision-support framework is then reviewed Delphi panels to ensure that it is complete and that it does, in fact, support decision-making related to AR.

Second, a Delphi Panel protocol was developed that outlined the Delphi process. This protocol included a full explanation of the project, an explanation of the Delphi study method, and a link to the survey that constitutes the first round of the Delphi study.

Finally, the authors developed a set of questions that would be presented to the Delphi panelists in the first round. In keeping with the Delphi method, these questions were designed to elicit informed opinions, expert insights, and potential areas of agreement or disagreement among panelists related to the preliminary decision-support framework that was developed and presented to the panelists in the first round. In addition, a set of different scenarios of AR application during different contextual factors were given with the questions to test the usability of the decision-support framework in different highway construction project contexts.

Overall, this initial material development phase was necessary to establish a solid foundation for the subsequent Delphi panel discussions and, ultimately, for enabling an informed decision-making process for highway construction project teams considering the implementation of AR on their projects.

4.5.2 Selection of Users

The Delphi rounds engaged two distinct groups of panelists: the first consisted of users who had already used AR on their highway construction projects, while the second group consisted of new users with no prior experience or very limited exposure (herein "users without prior experience") to implementing AR technology for communication on their highway construction projects. This approach allowed for a comprehensive evaluation, incorporating the perspectives of both experienced and inexperienced users in order to gather diverse insights and feedback on the framework application's performance. By including individuals who were unfamiliar with AR, the Delphi rounds provided an opportunity to assess the framework application's accessibility and ease of use for a broader user base, while also leveraging the expertise of those who had already interacted with the technology. The author contacted on-site and off-site Department of Transportation (DOT) personnel who used AR for communication during the first author's previous research (*8, 9*) to be the "users with previous experience".

Users without prior experience are chosen by the same DOT based on specific criteria to ensure their suitability for the Delphi panel. Criteria for suitability include:

1. Individuals who have ongoing interaction with construction sites. This ensures that they are familiar with construction site operations and can provide valuable insights.

2. Engineers or individuals with the capability to conduct inspections. Their technical expertise and knowledge of the construction site requirements make them invaluable contributors.

3. Consultants who are frequently contacted by the site with requests for information (RFIs) or site details are also chosen. These consultants possess a deep understanding of construction site needs and can offer specialized input.

By carefully selecting users based on these criteria, the aim is to gather a diverse and well-rounded group that can provide meaningful perspectives and contribute to the overall success of the project.

4.5.3 Delphi Panels

The implementation of this method involved conducting two rounds of Delphi panels with the two distinct user groups. The upcoming sections will outline the step-by-step process undertaken by the authors to execute this approach effectively.

The authors employed the Delphi technique to gather expert consensus on the preliminary decision-support framework using a survey and then a group discussion to collect panelists' feedback. Panelists were carefully selected as discussed above and presented with two rounds of questions to solicit their feedback.

First Round: Surveys

The authors created an introductory video that outlined the primary goals of the Delphi panels and the potential impact of its findings. (Essentially, this was a recording of the first author reading the "Protocol" discussed in the "Development of Initial Materials" section.) The video underwent editing and incorporated relevant graphics and images to ensure a complete understanding of the provided information. It served as the initial introduction to the survey that was given to panelists during this phase. Two separate surveys were created: one targeted panelist with prior experience in augmented reality (AR), while the other was designed for panelists with limited or no AR experience. The survey links were then distributed via email to all participants, who were given a two-week timeframe to complete them. This process marked the initial round of the Delphi panels.

The first-round survey consisted of questions related to the panelists' comprehension of the framework. To assess the panelists' understanding and their ability to make appropriate choices based on specific contexts and needs, four realistic scenarios were presented. Additionally, questions were included that focused on the format, workflow, and comprehensiveness of the decision-support framework (APPENDIX B, C). All responses were diligently recorded and considered during the analysis phase. These insights were used to refine and enhance the questions for the subsequent round of surveys.

Group Discussion Round

During the second round, live discussions were held with both the "users with experience" and "users without prior experience" panelists (APPENDIX D). The authors facilitated these discussions, incorporating the valuable insights gained from the first round, including the initial feedback provided by the panelists on the decision-support framework. To facilitate these discussions, the second round was conducted using the online platform Microsoft Teams, supporting clear communication and engagement among the panelists and the researchers. As a result, the discussion questions were updated and refined during the discussion to ensure the questions remained relevant and effectively captured the perspectives and feedback of the panelists as the discussion evolved. This interactive approach allowed for dynamic exchanges and deeper exploration of the subject matter, fostering a collaborative environment for further improvement and refinement of the research.

The collaborative discussions during the Delphi panel sessions allowed for the integration of different perspectives, enabling the authors to enhance the framework's effectiveness in guiding decision-making processes for users unfamiliar with AR technology.

4.5.4 Filtering Process

Following the completion of the two rounds of Delphi panels, the authors conducted a comprehensive review of all the responses provided by the participants. The answers from both the first and second rounds were thoroughly analyzed. The participants indicated that they were able to select and provide justifications for their technological tool choices in each of the four scenarios presented from among the factors in the decision-support framework. Moreover, the participants shared their opinions on AR application itself and provided feedback on the factors outlined in the framework.

The research team subsequently embarked on a filtering process to determine which factors could be incorporated into the decision-support framework. This filtering process was guided by two primary questions. First, the panelists evaluated whether the proposed factors would aid in decision-making when selecting a device to use to implement AR on active construction sites. Second, they considered whether or not a factor would be in the control of the target audience, e.g., on-site and off-site personnel working on a specific highway construction project. For instance, “cost of AR implementation” does not appear in the decision-support framework because the panelists agreed that these costs would not be project-specific costs that could be managed by the project team; rather, such costs would likely be overhead costs for the DOT and/or the contractor(s).

4.6 Results And Discussion

The first round of the Delphi panel comprised thirteen panelists from a state DOT, with five in the “users with experience” group and eight in the “users without prior experience” group. The second round involved the participation of five practitioners from the State DOT. Out of the five participants, four represented users who had never used augmented reality (AR) before, while one participant had prior experience with AR applications.

The diverse composition of the panelists proved beneficial for addressing the research team's questions and obtaining valuable feedback on framework development. The participant with firsthand experience of using AR on a construction site provided valuable insights to assess whether the framework's documented information aligned with their practical understanding of the technology. Simultaneously, the participants lacking previous AR experience also contributed their feedback, helping the authors to refine the framework and ensure its comprehensibility for users new to AR technology. Table 4. Shows the descriptions of the two types of users participating in the Delphi rounds.

Table 4: Panelist description participating in the Delphi panels.

	Role of panelist	
	Users with previous experience	Users without previous experience
Panelist involved in round1	5	8
Panelist involved in round2	1	4
Average experience years in the construction industry	2 between 10 and 15 years 3 between 15 and 20 years	3 between 10 and 15 years 5 between 15 and 20 years
Position	2 Project Managers 3 Superintendents	5 Professional Engineer 1 Safety Engineer 1 Maintenance Engineer 1 Geotechnical Engineer

Interestingly, the participants reached a consensus on the factors included in the framework, expressing no need for their removal. In fact, they even suggested the addition of new factors. After the filtration process, twenty-six factors were identified and organized into three sections to form the decision-support framework. Section 1 includes four mandatory factors, depicted in a process map in figure 2. Two types of tools supporting AR applications are included in the decision-support framework: Cellphone or Tablet based AR and Trimble XR10, or HoloLens-2 based AR. These two tools were the most used by practitioners during the exploration of the different factors as seen in previous studies (*8, 20, 21, 22, 23*). Section 2 comprises 12 factors that yield varying results depending on the type of device used for AR implementation. Lastly, section 3 includes 12 additional factors that do not differentiate between devices for AR implementation but provide additional details about the capabilities of various devices for AR implementation on construction sites.

4.6.1 Section 1: Mandatory Conditions

Among the factors that constitute the decision-support framework, four were deemed mandatory for proceeding with AR applications for synchronized communication. Without these essential elements, the implementation of AR would not be feasible. Fig.2 shows a process map for these factors.

After conducting a phone call from the site and realizing the need for enhanced interaction and visualization to obtain desired details for inspections or problem resolution, users must ensure the site can provide an appropriate internet connection, specifically a connection with a speed of more than 1.5 Mbps up/down, to facilitate an AR call. In the absence of an internet connection, it is advisable to opt for a site visit instead. If sufficient internet connectivity is available, users need to coordinate with each other. The on-site user should inform the off-site user that they will be initiating a call on AR-supported platforms. Once this coordination is established, AR implementation can proceed. Users should also be aware of the environmental conditions that can impact the efficacy of AR devices on-site, regardless of the device type. Temperature, in particular, plays a critical role in device performance, as no device can withstand temperatures above 95 degrees Fahrenheit. Similarly, it is important to note that during periods of high wind, AR devices may experience noise interference during calls, which can make it uncomfortable for both users to communicate effectively. At this stage, users should refer to Section 2 of the framework, which presents factors that differentiate headsets from cell phones for AR implementation. Finally, Section 3 provides more detailed performance information.

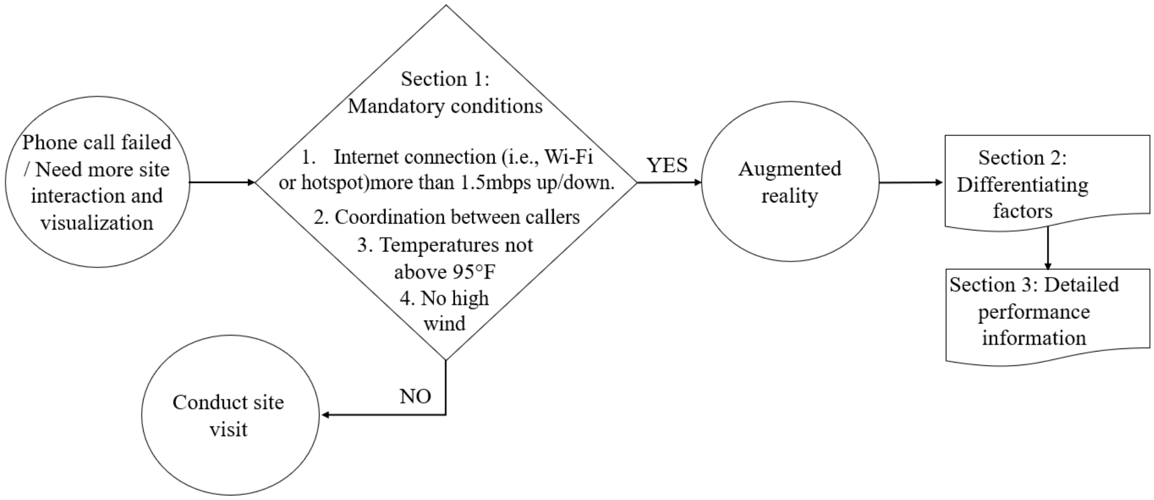


Figure 11: Process Map Showing Four Mandatory Factors for AR Application for Synchronized Communication.

4.6.2 Section 2: Differentiating Factors

This section of the framework demonstrates factors that perform differently depending on the AR implementation tool selected; as such, these factors significantly influence the decision-making process for users when selecting which AR implementation tool to use. This section is divided into three main parts: factors related to prerequisites, factors related to site conditions, and factors related to the AR specifications of each AR implementation device. The following subsections describe these factors in more detail.

	Factors	Cell-phone/ tablet based AR	Trimble XR-10- (HoloLens 2-) based AR
	related to pre-requisites		
1	Requires training sessions before use	NO	YES
2	Requires around 10 minutes set-up time	NO	YES
3	Requires transportation to the area of call	NO	YES
4	Requires protective safety awarness	NO	YES
	related to site conditions		
5	Functions at high temperatures above 86°F	●	⚠
6	Usable in bright sunlight	●	⚠
7	Usable in bright sunlight with shading device *	NA	●
8	Usable in light rain	⚠	●
	related to AR specifications		
9	Shares virtual drawings	⚠	●
10	Hands free operation	⚠	●
11	Supports communication while moving around site	⚠	●
12	Supports discussions about far and unreachable object of interest †	●	⚠

Legend	
●	Effective
⚠	Ineffective

NA: Not Applicable.

* Shading device: Crafted tinted film mask, installed at the front area of the holoLens.

† Object of interest: This refers to the location of the built element(s) or object(s) that are relevant to the discussion. For example, for a concrete column inspection call, the concrete column itself would be the point of interest.

Figure 12: Section 2 of the Decision-Support Framework

4.6.2.1 Factors related to pre-requisites.

It has been found that preparatory training sessions can be necessary when using head-mounted devices such as Trimble XR10 (*8*, *20*, *21*), primarily due to the virtual manipulation involved in supporting headsets. Previous studies have indicated that with practice and training, virtual manipulation can become more comfortable. Hence, training sessions are considered prerequisites for using headsets for AR implementation (*8*, *20*, *21*). However, this is not the case when choosing devices like cellphones and tablets, as users are generally more familiar with how to manipulate these devices, e.g., with touch screens or keyboards.

Additionally, due to the virtual manipulation and head mounting involved, setting up headsets typically takes about 10 minutes, including time for configuring the device, manipulating the interface, and launching the required software. However, this is not the case with Cellphone/Tablet-based AR. Launching AR-supported applications on Cellphones and Tablets can be generally faster as no installation process is required.

Unlike cellphones, which can be typically more accessible on construction sites as users often carry them in their pockets, headsets like the Trimble XR10 require transportation to the specific area where the call needs to be conducted. This makes cellphones more accessible than a headset or headsets when emergency calls are needed.

Due to headsets being head-mounted and covering the face and eyes, it becomes essential to raise safety awareness around users. This reduces the risk that hazards or work activities around the headset user will adversely affect them. However, this is not the case when using Cellphone or Tablet-based AR, as the user's line of sight remains unobstructed, allowing for better awareness of the user's surroundings and activities going on around the user.

4.6.2.2 Factors related to site conditions.

Site conditions have a profound impact on the AR implementation tools that support synchronized communication between onsite and offsite project stakeholders. Headsets are highly sensitive to heat, and if the temperature exceeds 86 degrees Fahrenheit (30 degrees Celsius), the device shuts down to prevent damage. On the other hand, cellphones and tablets tend to tolerate higher temperatures before shutting down or becoming non-operational.

Numerous studies have extensively documented the impact of sun brightness on headsets when used outdoors during daylight hours (*8*, *9*, *20*, *21*, *22*, *23*). Headsets rely on a virtual interface that can be difficult to see in bright sunlight. The use of shading devices can alleviate the impact of sunlight on headsets, resulting in improved visibility. These devices can help reduce the direct exposure of headsets to the sun, thereby enhancing the user's ability to see the virtual interface. In contrast, cellphones and tablets are manipulated through their screens, reducing concerns about the brightness of the sun affecting the manipulation or interface visibility.

Headsets used in construction sites, such as the Trimble XR10, are integrated with personal protective equipment (PPE) for safety reasons. The hard hat incorporated with this device serves to protect the front visor area of the headset, ensuring its effectiveness even during light rain. However, this level of protection would not be applicable to cellphones and tablets, as they would be directly exposed to water droplets, potentially affecting the visibility of their screens.

4.6.2.3 Factors related to AR specifications.

As mentioned earlier, headsets are operated through a virtual interface. During a synchronized call, headsets have the capability to incorporate virtual elements that are visible to all members of the session in real-time, appearing as if they exist overlaid on the existing environment (this is the case for onsite and offsite personnel). Unfortunately, this capability is not present in cellphones and tablets, where no virtual elements are seen overlaid on the existing environment. Only annotations can be made when using cellphones and tablets for AR implementation.

When headsets are worn on the head, they allow the wearer to have their hands free to perform other activities while conducting an AR call. In contrast, when using cellphones or tablets, users typically need at least one hand to hold the device, which limits their ability to multitask. This makes headsets more effective in terms of enabling the user to complete multiple tasks simultaneously.

During an AR call onsite, it is often necessary for users to have the ability to walk around and showcase various objects. Headsets, being head-mounted devices, can provide greater stability for the shared picture with the off-site user. This stability can ensure a clearer and steadier vision of the site. In contrast, cellphones and tablets, being handheld devices, might require more effort from the user to keep the device steady while moving around, potentially resulting in a shared picture that is less clear for the offsite viewer.

Headsets can allow the on-site user to share visuals from the site environment through the visor with any off-site user. However, when the object of interest is far away from the on-site user, it can be challenging for the off-site user to see that object clearly since it is also distant from the on-site user's perspective. In contrast, cellphones and tablets offer the advantage of zooming-in on the picture or shared vision since it is captured through the camera of the device. This zooming capability can make them more effective for inspections or examinations of objects or areas that may be far from the onsite user or otherwise physically inaccessible.

4.6.3 Section 3: Detailed Performance Information

The third section of the decision-support framework (Figure 4) showcases common factors that impact all types of tools, providing extra insights into their potential. It presents supplementary information and offers an understanding of each tool's capabilities. While these similarities may not significantly impact the decision-making process regarding the selection of a device to use for AR implementation, the panelists unanimously recognized the importance of these factors. They emphasized that all users should be aware of these factors both before and during the implementation of augmented reality (AR) on highway construction projects. The panelists deemed understanding and considering these factors important for effective and informed AR use. This section is structured similarly to Section 2 in that it comprises three main parts: factors related to prerequisites, factors related to site conditions, and factors related to AR specifications.

	Factors	Cell-phone/ tablet based AR	Trimble XR-10- (HoloLens 2-) based AR
	related to pre-requisites		
15	Requires safety training	NO	NO
	related to site conditions		
16	Usable in low light condition (night)	●	●
17	Usable with light dust	●	●
18	Usable in crowded areas	●	●
	related to AR specifications		
19	Can record calls	●	●
20	Supports calls with more than 2 users	●	●
21	Charges with external USB battery to extend operation time	●	●
22	Protects and secures collected data	●	●
23	Software supported by the device can be upgraded	●	●
24	High memory capacity to store data	●	●

Legend	
●	Effective

Figure 13: Section 3 of the Decision-Support Framework

4.6.3.1 Factors related to pre-requisites.

All panelists acknowledged and agreed that both head-mounted devices and cellphones do not require any safety training prior to their use for AR implementation on highway construction projects. While there are no apparent risks currently, the head-mounted devices used on-site come equipped with protective headgear, thereby reducing the potential hazards and risks that may be encountered. It is also possible that there are risks associated with technology, but due to its novelty, they may not yet be fully understood.

4.6.3.2 Factors related to site conditions.

Regarding site conditions, it is worth noting that both types of devices, namely head-mounted devices and cellphones/tablets, demonstrate compatibility with low light conditions. Similarly, they are both capable of functioning effectively in environments with light dust. Furthermore, both types of devices can be used in crowded areas. Headsets, worn on the head, enable users to have both hands free to navigate through crowds or manipulate objects around them while maintaining awareness of their surroundings for necessary movements. Similarly, users utilizing cellphones or tablets remain conscious of their environment and retain the ability to move around freely.

4.6.3.3 Factors related to AR specifications.

Both types of devices, head-mounted devices and cellphones/tablets, exhibit similarities in terms of their performance related to AR specifications as well. Firstly, both devices possess the capability to record calls and access those recordings later, facilitating information archiving, lessons learned, and scenario-based problem-solving exercises. The ability to record enables project stakeholders to preserve valuable insights and effectively address issues onsite. Additionally, both devices support calls with multiple participants, allowing for collaborative engagement during AR implementation. This multi-party calling feature enhances collaboration and aids in making informed decisions at the site. Both types of devices can be charged using external USB batteries, providing the opportunity to extend the duration of a call by prolonging the device's battery life. This feature supports uninterrupted communication during critical moments. Moreover, both devices prioritize data security, protecting the information shared during calls and maintaining the confidentiality of sensitive data. In turn, this feature can ensure a secure communication environment for users. Both types of devices rely on AR software applications, which can be upgraded and improved as needed. This flexibility allows for the incorporation of new features and enhancements to AR implementation as software improves. Lastly, both devices boast high memory capacities, enabling significant data storage and efficient data access.

4.7 AR Implementation to Improve Communication in the Construction Industry

In the construction industry, traditional communication methods often involve stakeholders initiating regular phone calls to address site issues, request information, or obtain additional data. However, if phone calls prove inadequate for resolving the matter, personnel tend to resort to scheduling site visits, which can lead to wasted time and expenses associated with traveling to and from remote sites. The introduction of augmented reality (AR) as a synchronous communication method offers a valuable alternative that bridges the gap between phone calls and site visits. By leveraging AR, practitioners can benefit from visual representations of site details, enhancing coordination efforts and facilitating the sharing of information. Figure 5 depicts the spectrum of communication methods commonly utilized in the construction industry, along with the placement of augmented reality (AR) within this spectrum.

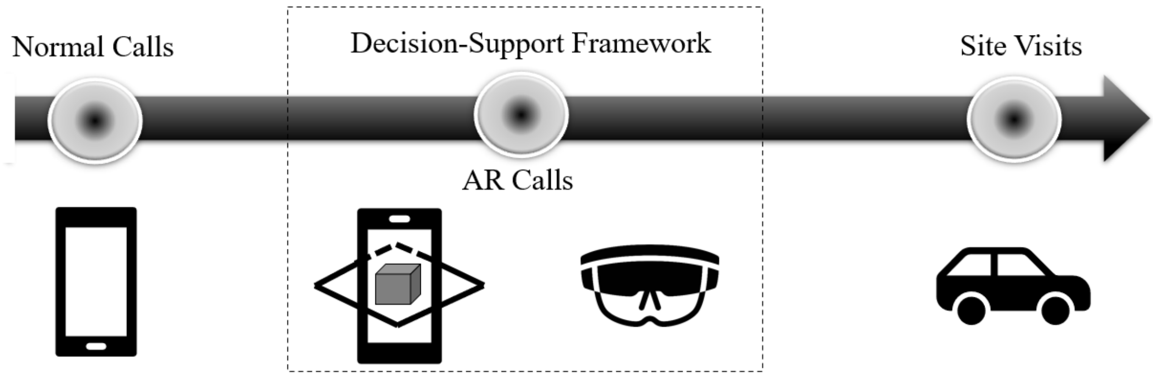


Figure 14: Communication Spectrum in the Construction Industry Introducing AR in the Middle of Traditional Methods.

The decision-support framework presented in this paper is aimed at supporting the implementation of this innovative communication method for highway construction projects, particularly those overseen by state Departments of Transportation (DOTs). By following the framework, highway construction project practitioners can effectively harness the capabilities of AR, enabling them to overcome the limitations of traditional communication methods. This empowers stakeholders to have real-time visual access to on-site information, improving coordination, reducing the need for physical site visits, and ultimately saving time and costs.

4.8 Conclusions

This paper leverages the knowledge accumulated from previous studies and consolidates the factors that impact the implementation of augmented reality (AR) for synchronized communication. It aims to provide highway construction project stakeholders on-site with a decision-support framework to assist them in selecting the appropriate device for AR implementation based on their situation and site conditions. By organizing and summarizing these factors, the paper offers valuable guidance to practitioners, enabling them to make informed decisions and optimize their AR implementation. This framework is structured in three distinct sections. The first section focuses on mandatory factors that are essential for the successful implementation of augmented reality (AR) calls. Without these factors in place, AR calls cannot be made. The second section of the framework comprises differentiating factors that highlight the prerequisites, site conditions, and AR specifications affecting the efficacy of AR implementation with each type of device. This section aims to provide practitioners with insights into the specific requirements and considerations associated with using different devices for AR implementation, enabling them to make informed decisions based on their unique situation and site conditions. The third section of the framework presents detailed performance information and illustrates similarities between device types for factors related to prerequisites, site conditions, and AR specifications. While these factors may not directly contribute to decision-making, they provide additional important information for users. This section aims to enhance users' understanding of how different devices perform AR implementation, similarly, contributing to a more comprehensive knowledge base.

Future studies can certainly build upon the framework presented in this paper by incorporating additional factors discovered through new research and the continuous development of AR technology. It is important to acknowledge that the current decision-support framework is based on exploratory factors identified in previous studies. While these factors provide a valuable starting point, they may not encompass all the variables that influence the implementation of AR. Moreover, the decision-support framework only considers AR implementation with a cellphone/tablet or with a headset. As additional devices support AR implementation, the decision-support framework may need new columns, and perhaps additional rows to capture these technologies (columns) and their capabilities in various contexts (rows). As AR technology evolves and is implemented in diverse and uncontrolled environments, new factors may emerge that impact its implementation. Future researchers will have the opportunity to uncover and explore these factors, further enhancing the framework and its usefulness. By conducting additional studies and gathering more empirical evidence, researchers can refine and expand the decision-support framework to encompass an even more comprehensive range of factors influencing the successful implementation of AR communication methods. Finally, this study leveraged Delphi panelists familiar with highway construction and road construction; it is possible that had the authors included Delphi panelists that are experts in building construction or industrial construction, different factors would have emerged. Acknowledging the limitations of this current study and the potential for new factors to be revealed highlights the importance of ongoing research in the field of AR implementation, ensuring that future decision-support frameworks are comprehensive and adaptable to the evolving nature of AR technology and its application in various construction contexts.

References

1. Gamil, Y.; Abdul Rahman, I. Identification of Causes and Effects of Poor Communication in Construction Industry: A Theoretical Review. Emerg. Sci. J. 2017, 1, 239–247.

2. Cheng, W. L. E., H. Li, P. E. Love, and Z. Irani. Network Communication in the Construction Industry. Corporate Communications: An International Journal, Vol. 6, No. 2, 2001, pp. 61–70

3. Minooei, F., N. Sobin, P. M. Goodrum, and K. R. Molenaar. Managing Public Communication Strategies in Accelerated Highway Construction Projects. Transportation Research Record: Journal of the Transportation Research Board, 2018. 2672: 1–10

4. Emmitt S. and Gorse C. Communication in Construction Teams. Taylor & Francis e-Library, 2006. DOI:10.4324/9780203018798

5. Azuma, R.T.A. Survey of Augmented Reality. Presence Teleoperators Virtual Environ. 1997, 6, 355–385.

6. Milgram, P., and F. Kishino. Taxonomy of Mixed Reality Visual Displays. IEICE Transactions on Information and Systems, Vol. 77, No. 12, 1994, pp. 1321–1329.

7. Berner, A. Augmented Reality the Past, the Present and the Future. Interaction Design Foundation (IxDF), 2020. https://interaction-design.org

8. Kassis, R.E.; Ayer, S.K.; Asmar, M.E.; Tang, P. Discovering Factors that Influence the Use of Augmented Reality for Communication on Active Highway Construction Sites. Transp. Res. Rec. 2022, 2677, 03611981221131311

9. El Kassis R., Steven K.A., and El Asmar M. Augmented Reality Applications for Synchronized Communication in Construction: A Review of Challenges and Opportunities. Applied Science MDPI. 2023. Volume 13, Issue 13, 7614

10. Diao, P.H.; Shih, N.J. Trends and research issues of augmented reality studies in architectural and civil engineering education—A review of academic journal publications. Appl. Sci. 2019, 9, 1840

11. Datcu, D.; Cidota, M.; Lukosch, H.; Lukosch, S. On the Usability of Augmented Reality for Information Exchange in Teams from the Security Domain. IEEE Jt. Intell. Secur. Inform. Conf. 2014, 160–167.

12. Wang, X.; Dunston, P.S. User perspectives on mixed reality tabletop visualization for face-to-face collaborative design review. Autom. Constr. 2008, 17, 399–412

13. Chalhoub, J.; Ayer, S.K. Using Mixed Reality for electrical construction design communication. Autom. Constr. 2018, 86, 1–10.

14. Zollmann, S.; Hoppe, C.; Kluckner, S.; Poglitsch, C.; Bischof, H.; Reitmayr, G. Augmented Reality for Construction Site Monitoring and Documentation. Proc. IEEE 2014, 102, 137–154.

15. Zhou, Y.; Luo, H.; Yang, Y. Implementation of augmented reality for segment displacement inspection during tunneling construction. Autom. Constr. 2017, 82, 112–121

16. Wang, X., and P. S. Dunston. Tangible Mixed Reality for Remote Design Review: A Study Understanding User Perception and Acceptance. Visualization in Engineering, Vol. 1, No. 1, 2013, pp. 1–15

17. Coˆte´, S., M. Beauvais, A. Girard-Vallee, and R. Snyde. A Live Augmented Reality Tool for Facilitating Interpretation of 2D Construction Drawings. In Proc., Lecture Notes in Computer Science: International Conference on Augmented and Virtual Reality, AVR 2014 (L. De Paolis and A. Mongelli, eds.), Vol. 8853, Lecce, Italy, September 17–20, 2014, Springer International Publishing, Switzerland, pp. 421–427. https://doi.org/10.1007/978-3-319-13969-2_32

18. Wang, X. Augmented Reality in Architecture and Design: Potentials and Challenges for Application. International Journal of Architectural Computing, Vol. 7, No. 2, 2009, pp. 309–326. https://doi.org/10.1260/147807709788921985

19. Shin, D. H., and P. S. Dunston. Evaluation of Augmented Reality in Steel Column Inspection. Automation in Construction, Vol. 18, No. 2, 2009, pp. 118–129.

20. El Kassis, R.; Ayer, S.K.; El Asmar, M.; Tang, P. Defining factors that support or hinder commercially available augmented reality (AR) devices for construction communication. In Proceedings of the Computing in Civil Engineering 2021, Orlando, FL, USA, 12–14 September 2021; pp. 1302–1310.

21. El Kassis, R.; Ayer, S.K.; El Asmar, M.; Tang, P. Augmented Reality Communication on Active Construction Sites: A Pilot Study Exploring Non-Technological Factors. In Proceedings of the Construction Research Congress 2022, Arlington, VA, USA, 9–12 March 2022; pp. 1202–1211

22. Chalhoub, J.; Ayer, S.K.; Ariaratnam, S.T. Augmented reality for enabling un-and under-trained individuals to complete specialty construction tasks. J. Inf. Technol. Constr. 2021, 26, 128–143

23. Wu, W.; Sandoval, A.; Gunji, V.; Ayer, S.K.; London, J.; Perry, L.; Patil, K.; Smith, K. Comparing traditional and mixed reality facilitated apprenticeship learning in a wood-frame construction lab. J. Constr. Eng. Manag. 2020, 146, 04020139

24. Delgado JM, D.; Oyedele, L.; Demian, P.; Beach, T. A research agenda for augmented and virtual reality in architecture, engineering and construction. Adv. Eng. Inform. 2020, 45, 101122.

25. Davila Delgado, J.M.; Oyedele, L.; Beach, T.; Demian, P. Augmented and virtual reality in construction: Drivers and limitations for industry adoption. J. Constr. Eng. Manag. 2020, 146, 04020079

26. Chen, K.; Chen, W.; Li, C.T.; Cheng, J.C. A BIM-based location aware AR collaborative framework for facility maintenance management. J. Inf. Technol. Constr. 2019, 24, 360–380

27. Aghajanian, J.; Prince, S. Face Pose Estimation in Uncontrolled Environments. In Proceedings of the British Machine Vision Conference, London, UK, 7–10 September 2009; Volume 1, p. 3.

28. Fenais, A.; Ariaratnam, S.T.; Ayer, S.K.; Smilovsky, N. Integrating geographic information systems and augmented reality for mapping underground utilities. Infrastructures 2019, 4, 60

29. Lin, J.R.; Cao, J.; Zhang, J.P.; van Treeck, C.; Frisch, J. Visualization of indoor thermal environment on mobile devices based on augmented reality and computational fluid dynamics. Autom. Constr. 2019, 103, 26–40.

30. Soria, G.; Ortega Alvarado, L.M.; Feito, F.R. Augmented and virtual reality for underground facilities management. J. Comput. Inf. Sci. Eng. 2018, 18, 041008

31. Thangaratinam, S., & Redman, C. W. The delphi technique. The obstetrician & gynaecologist, 2005, 7(2), 120-125

CHAPTER 5

Conclusion

In this dissertation three main chapters representing three papers were discussed, each featuring its distinct study design and individual outcomes. However, all three papers are interconnected and mutually supportive. Figure 15 illustrates the first figure in this dissertation in addition to the principal discoveries from these papers, which are then summarized and deliberated upon in the following sections.

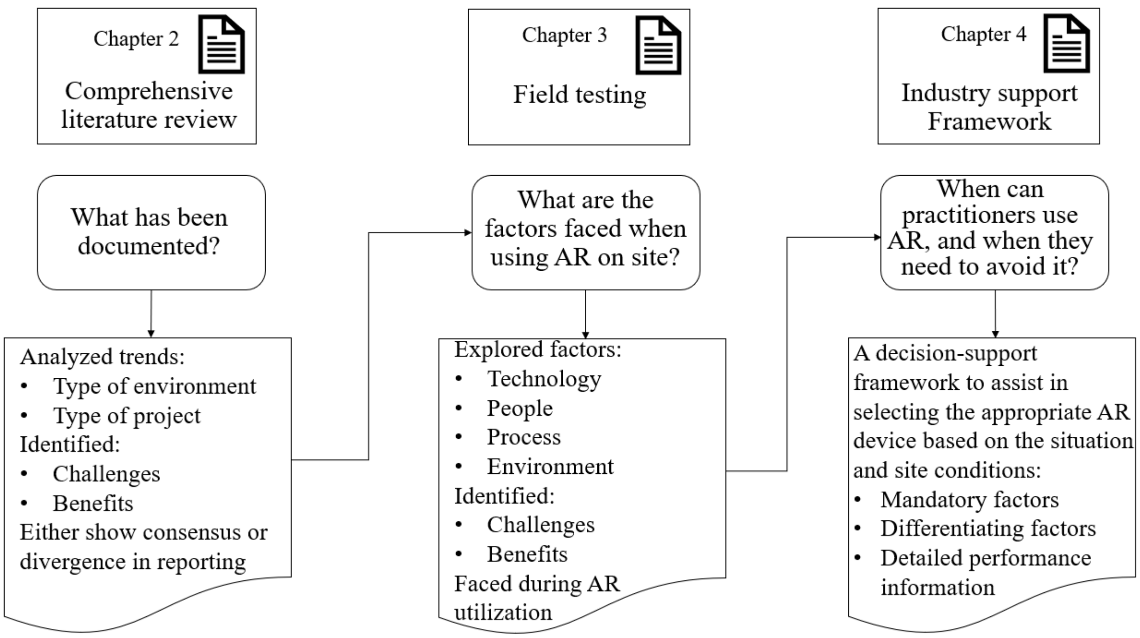


Figure 15: Representation of the Three Papers Presented, With the Motivating Questions and the Main Results.

5.1 Discussion of Papers

Chapter 2, delved into the existing literature to investigate the subject matter. It examined the patterns surrounding the utilization of Augmented Reality (AR) for facilitating coordinated communication among diverse stakeholders situated in remote locations. These patterns were categorized based on the nature of the settings and the specific projects, thereby shedding light on the challenges and benefits tied to the incorporation of AR as a communicative method. Within these trends, instances of agreement and discrepancy in reporting were observable. To comprehend these divergences, the author performed a comparative analysis. The majority of these instances of divergence were closely tied to contextual factors, underscoring the necessity for further exploration into the utilization of AR within real-time construction projects and the influence of these contexts on the effectiveness of AR applications. This observation underscores a gap that exists within current literature.

The following chapter aims to carry out field testing in order to investigate the factors influencing the utilization of Augmented Reality (AR) as a means of communication between on-site and off-site personnel on a horizontal project. A total of 14 factors were explored across various AR call videos. These recordings were supplemented by post-interviews with users. The collected data was subjected to thematic and perception analyses. The authors successfully categorized the identified factors into distinct groups encompassing technology, people, processes, and environment. Through this documentation, the paper highlights potential ways in which AR technologies can either immediately facilitate or hinder on-site communication for ongoing construction applications. While certain factors underscore the advantages of this technology, others present challenges.

Chapter 4 leverages the factors pinpointed in the preceding chapter to establish a comprehensive decision-making framework. This framework serves as a guiding tool for users, assisting them in the selection of the most suitable Augmented Reality (AR) device based on their specific circumstances and on-site conditions. By systematically arranging and summarizing these factors, the paper extends valuable insights to practitioners, empowering them to make well-informed choices that optimize their AR integration efforts. To validate the utility of this framework, the authors engaged in rounds of modified Delphi panels. These panels involved diverse scenarios presented to various panelists, evaluating the framework's usability. The first round of surveys gauged its effectiveness, while a subsequent round aimed to gather consensus on different aspects of the framework. The framework is structured into three distinct sections. The initial section centers on essential factors that form the bedrock for successful AR call implementation. In their absence, AR calls cannot be realized. The second segment encompasses differentiating factors, shedding light on prerequisites, site conditions, and AR specifications that impact the efficacy of AR deployment across various device types. This section equips practitioners with insights into specific demands and considerations tied to employing diverse devices for AR integration. This enables practitioners to make informed decisions, aligning with their individual contexts and site conditions. The third portion of the framework furnishes exhaustive performance details and draws parallels between device types concerning prerequisites, site conditions, and AR specifications. While these factors might not directly steer decision-making, they furnish crucial supplementary information for users. This segment aims to enhance users' comprehension of how distinct devices execute AR implementation, thereby contributing to a more comprehensive knowledge foundation.

5.2 Contributions

The three previously presented papers shared a cohesive motivation, where the elements of one paper seamlessly transitioned to the next. Alongside the shared motivational aspects, these papers also exhibited similar themes in their outcomes and contributions. The subsequent sections elucidate the interconnected overarching contributions of each of these papers.

A common theme running through these three papers is the importance of investigating the implementation of Augmented Reality (AR) in uncontrolled environments. The second chapter emphasizes trends and characteristics associated with both the environment and the project's type in which AR application was implemented. This chapter also delineates the challenges and benefits encountered during the deployment of this technology. On the other hand, the third chapter delves into the factors influencing the incorporation of AR for synchronized communication, particularly within uncontrolled environments and on highway projects. Building upon the factors previously examined and the insights synthesized from preceding sections, the fourth chapter devises a decision-making framework intended for on-site personnel utilization within the same contexts.

The primary outcome derived from these three chapters lies in the implementation of Augmented Reality (AR) technology knowledge extended to the industry. The second chapter encapsulates existing information scrutinized within the literature. Conversely, the third chapter seeks to uncover and explore new information and insights concerning the integration of AR technology in uncontrolled settings. Lastly, the fourth chapter assimilates this collective information into a tangible resource intended to guide and assist individuals operating within the same contextual factors in the industry.

5.3 Future Work

Subsequent AR developers and researchers have a promising foundation to expand upon, leveraging the results and analyses uncovered in each chapter.

This research establishes groundwork by outlining benefits, challenges, and contextual factors. Moving forward, future endeavors could strategically capitalize on this knowledge, effectively incorporating or avoiding specific settings during AR implementation, thus maximizing the advantageous elements reported in existing literature.

Also, this research uncovers the hurdles encountered in a live AR application, it offers valuable material for forthcoming investigations. These challenges serve as a sturdy cornerstone for future studies, potentially inspiring both practitioners and researchers to confront the identified obstacles head-on and devise robust solutions not only within horizontal projects but could also expand to all type of construction projects. To elaborate on environment-related drawbacks such as remote area internet connectivity, summer sun glare, and construction site noise, upcoming research could delve into innovative technical solutions to overcome these challenges. Moreover, in addressing other identified challenges, forthcoming studies could concentrate on training workshops that simulate uncontrolled real-world environments.

Additionally, this research constructs an instructional framework to aid users in selecting the optimal AR-compatible device based on specific scenarios and conditions they encounter could be a viable avenue for future research. Forthcoming investigations can undoubtedly build upon the framework outlined in this study by integrating additional factors unearthed through fresh research endeavors and the continual advancement of AR technology. It is crucial to recognize that the existing decision-support framework is grounded in exploratory factors identified in earlier studies. While these factors offer a valuable initial foundation, they might not encompass the entirety of variables influencing AR implementation. Furthermore, the decision-support framework currently focuses solely on AR implementation using either a cellphone/tablet or a headset. As more devices extend support for AR deployment, it may be necessary to introduce new columns and potentially additional rows to the framework to account for these emerging technologies (columns) and their capabilities within diverse contexts (rows).

As AR technology evolves and finds its way into varied and uncontrollable environments, novel factors could arise, exerting an impact on its implementation. Subsequent researchers will have the opportunity to unearth and explore these emerging factors, thereby augmenting the framework's efficacy and utility. By carrying out further studies and accumulating more empirical evidence, researchers can hone and expand the decision-support framework to encompass an even more comprehensive array of influences shaping the successful integration of AR communication methodologies.

Lastly, this study relied on data collected from personnel with expertise in highway and road construction; it remains plausible that incorporating further studies versed in vertical construction or industrial construction might have yielded different factors. Acknowledging the limitations inherent in this study and the potential for new factors to emerge underscores the significance of ongoing research in the realm of AR implementation. This ensures that forthcoming decision-support frameworks remain comprehensive and adaptable to the evolving nature of AR technology and its deployment across various construction contexts.

REFERENCES

A Gamil, Y., and Abdul Rahman, I. (2017). "Identification of Causes and Effects of Poor Communication in Construction Industry: A Theoretical Review". Emerging Science Journal. Vol.1, no.4.

Aghajanian, J.; Prince, S. Face Pose Estimation in Uncontrolled Environments. In Proceedings of the British Machine Vision Conference, London, UK, 7–10 September 2009; Volume 1, p. 3.

Ahmed, S. A review on using opportunities of augmented reality and virtual reality in construction project management. Organ. Technol. Manag. Constr. Int. J. 2018, 10, 1839–1852.

ASCE American Society of Civil Engineers. Future World Vision: Infrastructure Reimagined; 2019. Future World Vision: Infrastructure Reimagined (asce.org)

Azuma, R. T. A. (1997). "Survey of Augmented Reality." Presence: Teleoperators and 155 Virtual Environments.

Bae, H.; Golparvar-Fard, M.; White, J. High-precision vision-based mobile augmented reality system for context-aware architectural, engineering, construction and facility management (AEC/FM) applications. Vis. Eng. 2013, 1, 3. Available online: http://www.viejournal.com/content/1/1/3 accessed on 09 November 2022.

Behzadan, A. H., and Kamat, V. R. Visualization of Construction Graphics in Outdoor Augmented Reality. Proceedings of the Winter Simulation Conference, IEEE, Orlando, FL. USA; 2005. 1914-1920.

Behzadan, A. H., and Kamat, V. R. Simulation and visualization of traffic operations in Augmented Reality for improved planning and design of road construction projects. Winter Simulation Conference, IEEE, Miami, FL, USA; 2008. 2447–2454.

Bellare, J.; Davis, H.T.; Scriven, L.E.; Talmon, Y. Controlled environment vitrification system: An improved sample preparation technique. J. Electron Microsc. Tech. 1988, 10, 87–111.

Berner A. Augmented Reality The Past, The Present and The Future. Interaction Design Foundation (IxDF); 2020. interaction-design.org

Braun, V. & Clarke, V. Using thematic analysis in psychology. Qualitative Research in Psychology; 2006. 3,77-101.

Briner, R.B.; Denyer, D. Systematic review and evidence synthesis as a practice and scholarship tool. In Handbook of Evidence-Based Management: Companies, Classrooms and Research; Oxford University Press: Oxford, UK, 2012; pp. 112–129.

Broll W., Lindt, I. et al. ARTHUR: A collaborative augmented environment for architectural design and urban planning. Journal of Virtual Reality and Broadcasting; 2004. Vol.1, no.1.

Clarke, V. and Braun, V. Teaching thematic analysis: Overcoming challenges and developing strategies for effective learning. The Psychologist; 2013. *26*(2),120-123.

Chalhoub, J., and Ayer, S. K. Using Mixed Reality for electrical construction design communication. Automation in Construction; 2018. 86,1–10

Chalhoub, J., and Ayer, S. K. Exploring the performance of an augmented reality application for construction layout tasks. Multimedia tools and applications; 2019. Vol.78(24). https://doi.org/10.1007/s11042-019-08063-5

Chalhoub, J.; Ayer, S.K.; Ariaratnam, S.T. Augmented reality for enabling un-and under-trained individuals to complete specialty construction tasks. J. Inf. Technol. Constr. 2021, 26, 128–143.

Chen, Y.C.; Chi, H.L.; Kang, S.C.; Hsieh, S.H. Attention-based user interface design for a tele-operated crane. J. Comput. Civ. Eng. 2016, 30, 04015030.

Chen, K.; Chen, W.; Li, C.T.; Cheng, J.C. A BIM-based location aware AR collaborative framework for facility maintenance management. J. Inf. Technol. Constr. 2019, 24, 360–380.

Chen C.P. J., Chen K. and Chen W. State-of-the-Art Review on Mixed Reality Applications in the AECO Industry. Journal of Construction Engineering and Management, ASCE; 2020. V146, Issue 2. DOI: 10.1061/(ASCE)CO.1943-7862.0001749

Cheng W. L. E., Li H., et al. Network communication in the construction industry. Corporate Communications: An International Journal; 2001. Vol.6, nb.2.61-70. ISSN1356-3289

Chi, H.L.; Kang, S.C.; Wang, X. Research trends and opportunities of augmented reality applications in architecture, engineering, and construction. Autom. Constr. 2013, 33, 116–122.

Chung, S.; Cho, C.S.; Song, J.; Lee, K.; Lee, S.; Kwon, S. Smart facility management system based on open bim and augmented reality technology. Appl. Sci. 2021, 11, 10283.

Construction Data. The Construction Association of America; 2018

Côté, S., Trudel P., Desbiens M-A., Giguere M., and Snyde R. Live Mobile Panoramic High Accuracy Augmented Reality for Engineering and Construction. Proceedings of the 13th International Conference on Construction Applications of Virtual Reality; 2013. 30-31, London, UK.2

Côté, S., Beauvais M., Girard-Vallée A., and Snyde R. A Live Augmented Reality Tool for Facilitating Interpretation of 2D Construction Drawings. Springer International Publishing Switzerland; 2014. LNCS 8853. DOI:10.1007/978-3-319-13969-2_32

Cote, S., and Mercier, A. Augmentation of Road Surfaces with Subsurface Utility Model Projections. IEEE Conference on Virtual Reality and 3D User Interfaces (VR); 2018. Reutlingen,535–536.

Criollo-C, S.; Abad-Vásquez, D.; Martic-Nieto, M.; Velásquez-G, F.A.; Pérez-Medina, J.L.; Luján-Mora, S. Towards a new learning experience through a mobile application with augmented reality in engineering education. Appl. Sci. 2021, 11, 4921.

Dainty A., Moore D. and Murray M. Communication in construction, theory and practice. Taylor&Francis, London; 2006. DOI:10.4324/9780203358641

Datcu, D.; Cidota, M.; Lukosch, H.; Lukosch, S. On the Usability of Augmented Reality for Information Exchange in Teams from the Security Domain. IEEE Jt. Intell. Secur. Inform. Conf. 2014, 160–167. DOI: 10.1109/JISIC.2014.32

Davila Delgado, J.M.; Oyedele, L.; Beach, T.; Demian, P. Augmented and virtual reality in construction: Drivers and limitations for industry adoption. J. Constr. Eng. Manag. 2020, 146, 04020079.

Delgado JM, D.; Oyedele, L.; Demian, P.; Beach, T. A research agenda for augmented and virtual reality in architecture, engineering and construction. Adv. Eng. Inform. 2020, 45, 101122.

Denyer, D.; Tranfield, D. Producing a systematic review. In The SAGE Handbook of Organizational Research Methods; SAGE: London, UK, 2009.

Diao, P.H.; Shih, N.J. Trends and research issues of augmented reality studies in architectural and civil engineering education—A review of academic journal publications. Appl. Sci. 2019, 9, 1840.

Diao, P.H.; Shih, N.J. BIM-based AR maintenance system (BARMS) as an intelligent instruction platform for complex plumbing facilities. Appl. Sci. 2019, 9, 1592.

Dinis, F.M.; Guimarães, A.S.; Carvalho, B.R.; Martins, J.P.P. Virtual and augmented reality game-based applications to civil engineering education. In Proceedings of the 2017 IEEE Global Engineering Education Conference (EDUCON), Athens, Greece, 25–28 April 2017; IEEE: Piscataway, NJ, USA, 2017; pp. 1683–1688.

Dunston, P., Wang, X., Billinghurst, M., and Hampson, B. Mixed Reality Benefits for Design Perception. Washington, DC, USA; 2003

El Ammari, K.; Hammad, A. Remote interactive collaboration in facilities management using BIM-based mixed reality. Autom. Constr. 2019, 107, 102940.

El Asmar, G.P.; Chalhoub, J.; Ayer, K.S.; Abdallah, A.S. Contextualizing Benefits and Limitations Reported for Augmented Reality in Construction Research. J. Inf. Technol. Constr. 2021, 26, 720–738. https://doi.org/10.36680/j.itcon.2021.039.

El Kassis, R.; Ayer, S.K.; El Asmar, M.; Tang, P. Defining factors that support or hinder commercially available augmented reality (AR) devices for construction communication. In Proceedings of the Computing in Civil Engineering 2021, Orlando, FL, USA, 12–14 September 2021; pp. 1302–1310.

El Kassis, R.; Ayer, S.K.; El Asmar, M.; Tang, P. Augmented Reality Communication on Active Construction Sites: A Pilot Study Exploring Non-Technological Factors. In Proceedings of the Construction Research Congress 2022, Arlington, Virginia, 9–12 March 2022; pp. 1202–1211.

El Kassis R., Steven K.A., and El Asmar M. Augmented Reality Applications for Synchronized Communication in Construction: A Review of Challenges and Opportunities. Applied Science MDPI. 2023. Volume 13, Issue 13, 7614

Emmitt, S., and Gorse, C. (2006). Communication in Construction Teams. Taylor & Francis eLibra

Fenais, A.; Smilovsky, N.; Ariaratnam, S.T.; Ayer, S.K. (2018, March). A meta-analysis of augmented reality challenges in the underground utility construction industry. In Proceedings of the Construction Research Congress 2018, New Orleans, LA, USA, 2–4 April 2018; pp. 80–89.

Fenais, A.; Ariaratnam, S.T.; Ayer, S.K.; Smilovsky, N. Integrating geographic information systems and augmented reality for mapping underground utilities. Infrastructures 2019, 4, 60.

Fenais, A.S.; Ariaratnam, S.T.; Ayer, S.K.; Smilovsky, N. A review of augmented reality applied to underground construction. J. Inf. Technol. Constr. 2020, 25, 308–324.

Ganah A., Anumba C. J., Bouchlaghem N. M. Computer Visualisation as a Communication Tool in the Construction Industry. Proceedings Fifth International Conference on Information Visualization; 2001.

Gann, D.M. Building Innovation: Complex Constructs in a Changing World; Thomas Telford Publications: London, UK, 2000.

GCR, N. (2004). Cost analysis of inadequate interoperability in the US capital facilities industry. National Institute of Standards and Technology (NIST), 223-253.

Goh, K C Goh, H H, Toh, S H and Peniel A. Enhancing communication in construction industry through BIM. Proceedings of the 11th International Conference on Innovation & Management; 2014. PP (313-324)

Guest G., Namey E., and Chen M. A simple method to assess and report thematic saturation in qualitative research. PLoS ONE; 2020. https://doi.org/10.1371/journal.pone.0232076

Gurevich, P., Lanir, J., Cohen, B., & Stone, R. (2012, May). TeleAdvisor: a versatile augmented reality tool for remote assistance. In Proceedings of the SIGCHI conference on human factors in computing systems (pp. 619-622).

Harikrishnan, A.; Abdallah, A.S.; Ayer, S.K.; El Asmar, M.; Tang, P. Feasibility of augmented reality technology for communication in the construction industry. Adv. Eng. Inform. 2021, 50, 101363.

Hoezen M.E.L., Reymen I.M.M.J., Dewulf G.P.M.R. (2007). The Problem of Communicationin Construction. University of Twente. The_problem_of_communication_in_construc20160123-5854-1wtyk0i-libre.pdf (d1wqtxts1xzle7.cloudfront.net)

Honkamaa, P., Siltanen, S., Jäppinen, J., Woodward, C., & Korkalo, O. (2007, April). Interactive outdoor mobile augmentation using markerless tracking and GPS. In Proc. Virtual Reality International Conference (VRIC) (pp. 285-288).

Hou, L.; Wang, X.; Bernold, L.; Love, P.E. Using animated augmented reality to cognitively guide assembly. J. Comput. Civ. Eng. 2013, 27, 439–451.

Hou, L.; Chi, H.L.; Tarng, W.; Chai, J.; Panuwatwanich, K.; Wang, X. A framework of innovative learning for skill development in complex operational tasks. Autom. Constr. 2017, 83, 29–40.

Hull, D.M.; Saxon, T.F. Negotiation of meaning and co-construction of knowledge: An experimental analysis of asynchronous online instruction. Comput. Educ. 2009, 52, 624–639.

Importance of Construction Industry in The Economy and The Use of Construction Equipment. Holloway. 2018; Importance Of Construction Industry In The Economy And Use Of Construction Equipments - Blog (hhilifting.com)

Kassis, R.E.; Ayer, S.K.; Asmar, M.E.; Tang, P. Discovering Factors that Influence the Use of Augmented Reality for Communication on Active Highway Construction Sites. Transp. Res. Rec. 2022, 2677, 03611981221131311.

Kazi, A.S. Knowledge management in the construction industry: A socio-technical perspective. IGI Global. Technology & Engineering; 2005. p.384. DOI: 10.4018/978-1-59140-360-9

Kim, D.; Choi, Y. Applications of smart glasses in applied sciences: A systematic review. Appl. Sci. 2021, 11, 4956.

Kim, K., Kim, H., and Kim, H. Image-based construction hazard avoidance system using augmented reality in wearable device. Automation in Construction; 2017.

Kim, M.J. A framework for context immersion in mobile augmented reality. Autom. Constr. 2013, 33, 79–85.

Kwon, O.S.; Park, C.S.; Lim, C.R. A defect management system for reinforced concrete work utilizing BIM, image-matching and augmented reality. Autom. Constr. 2014.

Labra O., Castro C., Wright R. and Chamblas I. Thematic Analysis in Social Work: A Case Study. Cutting Edge Issues and Critical Reflections, Bala Raju Nikku, IntechOpen; 2019. DOI:10.5772/intechopen.89464.

Lee, J.G.; Seo, J.; Abbas, A.; Choi, M. End-Users' augmented reality utilization for architectural design review. Appl. Sci. 2020, 10, 5363.

Lee, S. and Yu J. Longitudinal Study on Construction Organization's BIM Acceptance. Applied sciences; 2020. doi:10.3390/app10155358

Li, X.; Yi, W.; Chi, H.L.; Wang, X.; Chan, A.P. A critical review of virtual and augmented reality (VR/AR) applications in construction safety. Autom. Constr. 2018, 86, 150–162.

Lin, T.-H., Liu, C.-H., Tsai, M.-H., and Kang, S.-C. Using Augmented Reality in a Multiscreen Environment for Construction Discussion. Journal of Computing in Civil Engineering; 2015. 29(6),04014088.

Lin, J.R.; Cao, J.; Zhang, J.P.; van Treeck, C.; Frisch, J. Visualization of indoor thermal environment on mobile devices based on augmented reality and computational fluid dynamics. Autom. Constr. 2019, 103, 26–40.

Meža, S.; Turk, Ž.; Dolenc, M. Component based engineering of a mobile BIM-based augmented reality system. Autom. Constr. 2014, 42, 1–12.

Milgram, P., and Kishino, F. Taxonomy of mixed reality visual displays. IEICE Transactions on Information and Systems; 1994. 1321–1329

Minooei F., et al. Managing Public Communication Strategies in Accelerated Highway Construction Projects. Journal Of the Transportation Research Board; 2018. https://doi.org/10.1177/0361198118759943

Moira Maguire & Brid Delahunt. Doing a Thematic Analysis: A Practical, Step-by-Step Guide for Learning and Teaching Scholars. All Ireland Journal of Teaching and Learning in Higher Education; 2017. http://ojs.aishe.org/index.php/aishe-j/article/view/335

Moreu, F., Lippitt, C., Maharjan, D., Aguero, M., and Yuan, X. Augmented Reality Enhancing the Inspections of Transportation Infrastructure: Research, Education, and Industry Implementation; 2019

Park C-S. and Kim H-J. A framework for construction safety management and visualization system. Automation in Construction; 2013. 33,95–103

Patil, K.R.; Ayer, S.K.; Wu, W.; London, J. Mixed reality multimedia learning to facilitate learning outcomes from project-based learning. In Proceedings of the Construction Research Congress 2020: Computer Applications, Tempe, Arizona, 8–10 March 2020; American Society of Civil Engineers: Reston, VA, USA, 2020; pp. 153–161.

Pheng L.S. and Hou L.S. The Economy and the Construction Industry. Construction Quality and the Economy; 2019. 21-54. DOI:10.1007/978-981-13-5847-0_2

Radu, I. Augmented reality in education: A meta-review and cross-media analysis. Pers. Ubiquitous Comput. 2014, 18, 1533–1543.

Rankohi, S.; Waugh, L. Review and analysis of augmented reality literature for construction industry. Vis. Eng. 2013, 1, 9.

Roberts, D. G. W., Evans, A., Dodson, A. H., Cooper, S., and Hollands, D. R. The Use of Augmented Reality, GPS and INS for Subsurface Data Visualization; 2002

Salamak M. and Januszka M. BIM Models and Augmented Reality for Concrete Bridge Inspections. 11th CCC Congress HAINBURG; 2015. DOI:10.13140/RG.2.1.5161.0329

Shin, D. H., and Dunston, P. S. Evaluation of Augmented Reality in steel column inspection. Automation in Construction; 2009. 18(2),118–129.

Soria, G., Ortega Alvarado, L. M., & Feito, F. R. (2018). Augmented and virtual reality for underground facilities management. Journal of Computing and Information Science in Engineering, 18(4).

Sperber D. and Wilson D. Communication and Cognition. Blackwell's, Oxford; 1986

Tayeh, R.; Issa, R.R. Interactive holograms for construction coordination and quantification. J. Manag. Eng. 2020, 36, 04020079.

Thangaratinam, S., & Redman, C. W. (2005). The delphi technique. The obstetrician & gynaecologist, 7(2), 120-125

Vidal-Balea, A.; Blanco-Novoa, O.; Fraga-Lamas, P.; Vilar-Montesinos, M.; Fernández-Caramés, T.M. Creating collaborative augmented reality experiences for industry 4.0 training and assistance applications: Performance evaluation in the shipyard of the future. Appl. Sci. 2020, 10, 9073.

Vogt W. P., Gardner C.D., Haeffele L.M. and Vogt E. R. Selecting the Right Analyses for Your Data: Quantitative, Qualitative, and Mixed Methods. Guilford Publications -Social Science; 2014

Wang, X.; Dunston, P.S. User perspectives on mixed reality tabletop visualization for face-to-face collaborative design review. Autom. Constr. 2008, 17, 399–412.

Wang X. Augmented Reality in Architecture and Design: Potentials and Challenges for Application. SAGE Journal; 2009. https://doi.org/10.1260/147807709788921985

Wang, X., and Dunston, P. S. Tangible mixed reality for remote design review: a study understanding user perception and acceptance. Visualization in Engineering; 2013. 1:8

Wang, T.-K.; Huang, J.; Liao, P.-C.; Piao, Y. Does Augmented Reality Effectively Foster Visual Learning Process in Construction? An Eye-Tracking Study in Steel Installation. Adv. Civ. Eng. 2018, 2018, 2472167. https://doi.org/10.1155/2018/2472167.

Woodward, C., Hakkarainen, M., Korkalo, O., Kantonen, T., Aittala, M., Rainio, K., & Kähkönen, K. (2010, November). Mixed reality for mobile construction site visualization and communication. In Proc. 10th International Conference on Construction Applications of Virtual Reality (CONVR2010) (pp. 4-5).

Wu W., Sandoval A., Gunji V., Ayer S., London J., Perry L., Patil K., and Smith K. Comparing Traditional and Mixed Reality-Facilitated Apprenticeship Learning in a Wood-Frame Construction Lab. ASCE; 2021. DOI:10.1061/(ASCE)CO.1943-7862.0001945

Yeh, K.C.; Tsai, M.H.; Kang, S.C. On-site building information retrieval by using projection-based augmented reality. J. Comput. Civ. Eng. 2012, 26, 342–355.

Zhou, Y.; Luo, H.; Yang, Y. Implementation of augmented reality for segment displacement inspection during tunneling construction. Autom. Constr. 2017, 82, 112–121.

Zollmann, S.; Hoppe, C.; Kluckner, S.; Poglitsch, C.; Bischof, H.; Reitmayr, G. Augmented Reality for Construction Site Monitoring and Documentation. Proc. IEEE 2014, 102, 137–154.

APPENDIX A

INSTRUCTIONAL GUIDE

QUICK START GUIDE: **On-Site Users**

Open the HOLOLENS case. Remove the HOLOLENS with its charger. Charge it for a minimum of 30 minutes (if it has not been charged yet).

Clean the interior area of the helmet with sanitizing wipes. Clean the HoloLens glass with the dry glass wipe.

Put the HoloLens on your head and adjust it with the rotating wheel on the back for your comfort. Drop down the glass. Push the start button on the back.

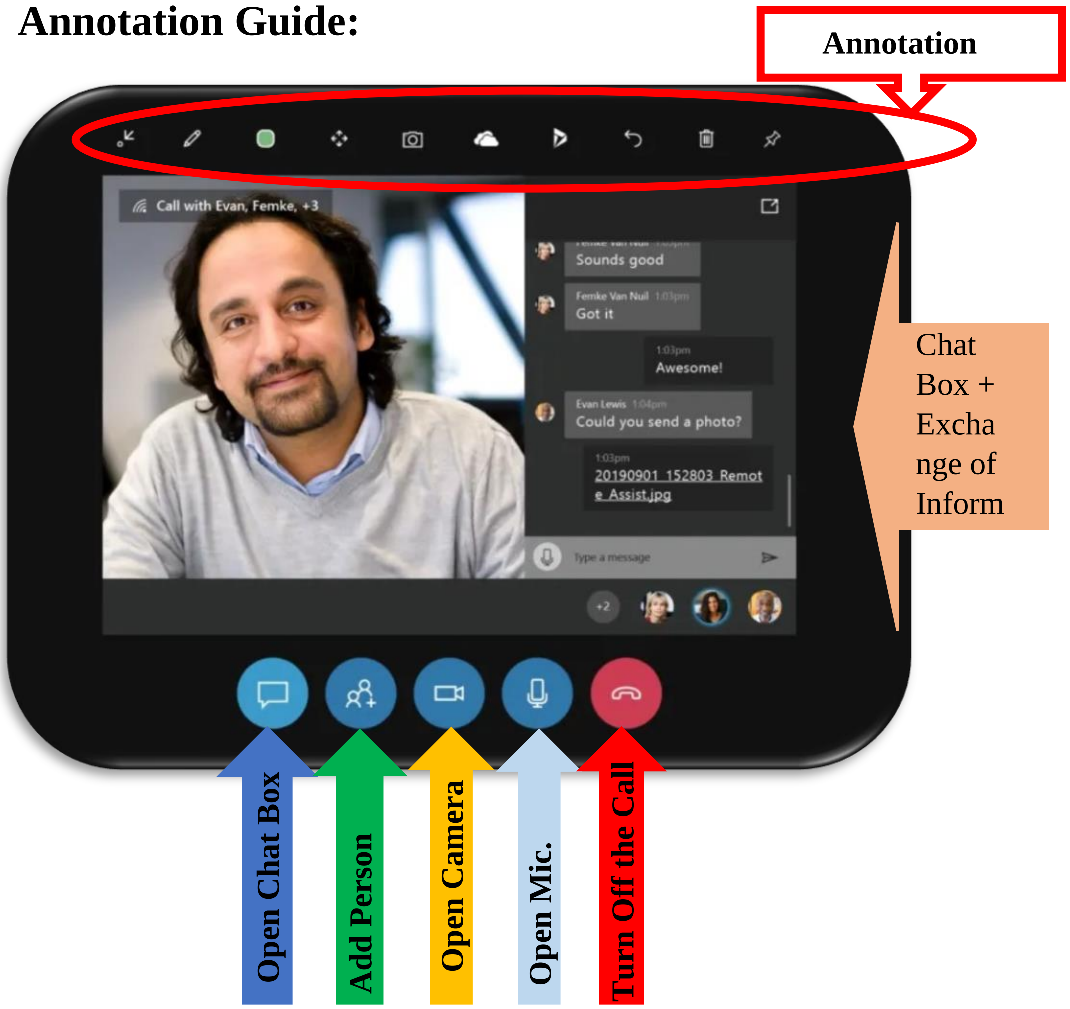
Connect the device to an Internet Wi-Fi connection using the Settings function. Turn the Headphones Power On. Connect the Headphones using Bluetooth connection, if it has not been connected automatically.

Enter the given Pin Code to access the device. Watch the tutorial video for quick manipulation instructions of the HoloLens. Make sure that *Microsoft Dynamics 365 Remote Assist* is downloaded on the device, if not, you can download it from the *Microsoft Store*.

Before launching any calls, make sure that the person you want to call is online or available on *Microsoft Teams* on their computer. Click on *Microsoft Dynamics 365 Remote Assist* and launch the application on the device. Search your contacts to find the off-site person you want to call and launch the call.

After calling the person off-site, click on the "add contact" icon for the possibility to more people on the call. Search in your contact and click on their name and call them.

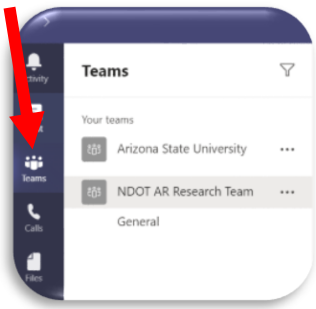
Annotation Guide:

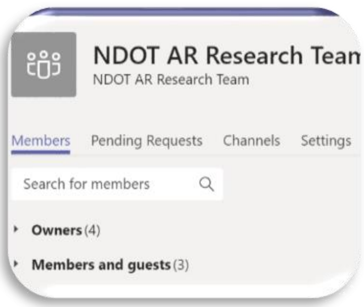


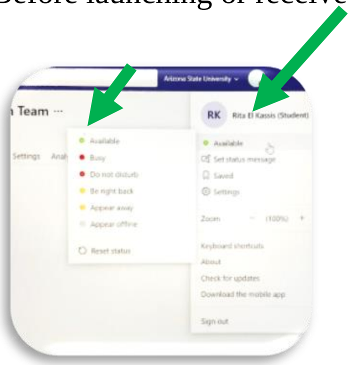
QUICK START GUIDE: **Off-Site Users**

The off-site participants should have *Microsoft Teams* installed on their NDOT Laptop or computer that will be used for the call.

Make sure you are in the right group on *Microsoft Teams*. Before launching or receive a call, make sure your status is shown as available.







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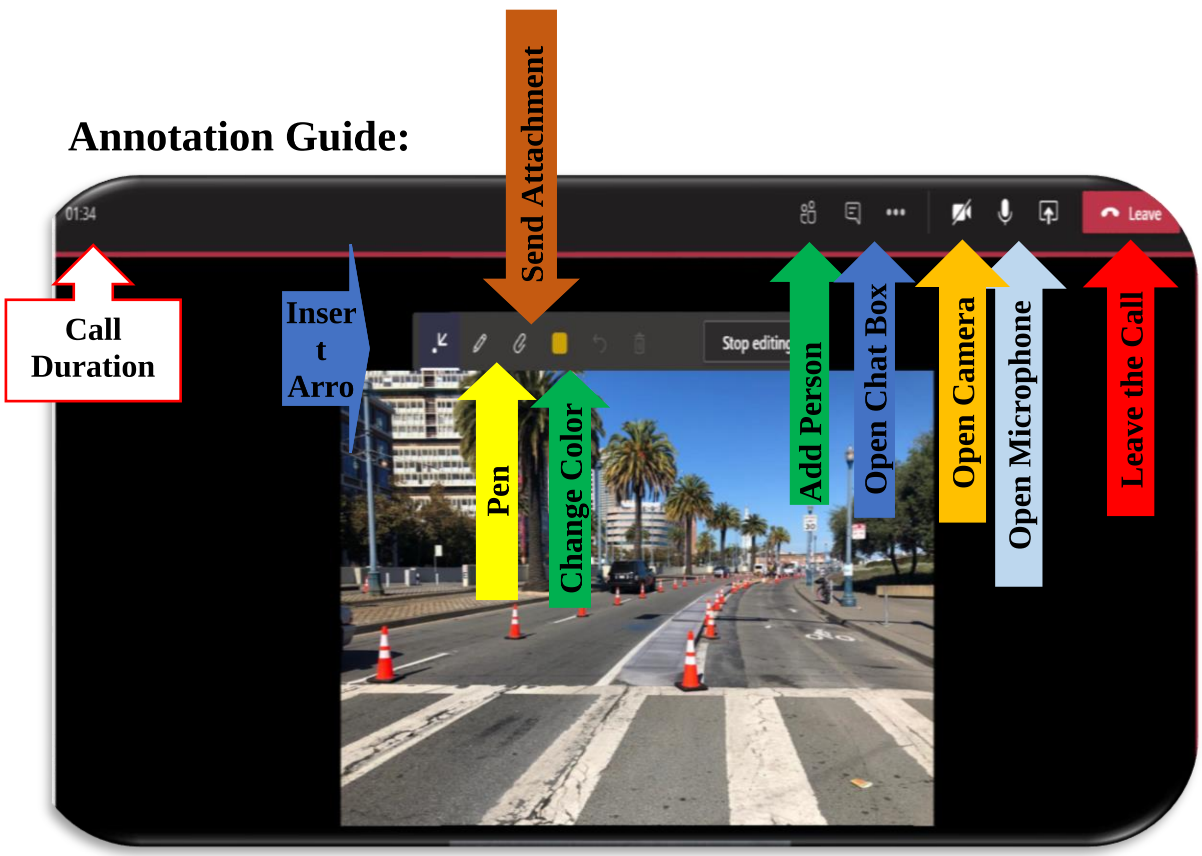

Helpful Tips and Tricks

- After finishing the call, please make sure to turn off the device the same way you turned it on. Clean the interior of the hard hat with wipes and charge it again for the next use.
- If you require extended power while using the HoloLens, you can connect the included power bank via USB cable and store the power bank in a back pocket while in use.
- While making annotations, the image captured from the on-site user will freeze allowing the off-site user to annotate on a static image. Make sure to inform the on-site user that annotation will occur, so he or she will notice the annotation.
- After annotations are completed by the off-site user, the image from the on-site user will return to a live video feed.
- When a video call is launched a conversation box will be opened directly between the two contacts. Annotations created during a call can be saved in the same chat box.
- For your safety, please do not use the HoloLens during extreme heat events.
- While inserting annotations of both lines and arrows, current site conditions should be considered. For example:
    - Yellow is not ideal under sun glare.
    - Red is not a good color to use while annotating on a red object.
    - When inserting an arrow, make sure to widen the scale of it in order to become visible for both users. Use a hand gesture to widen the arrow.
- While sharing files its always recommended to place the open content in a shaded area. Use a hand gesture to move the file into the desired area. In instances when no shade is present, it is better to open files away from the direction of the sun to avoid washout from the sun’s backlighting.
- For outdoor usage under the sun glare, use the tinted-film glass cover:
    - Lighter tint for moderately sunny days.
    - Darker tint for very sunny days.

APPENDIX B

SURVEY QUESTIONS FOR USERS WITH PREVIOUS EXPERIENCE - DELPHI PANEL ROUND 1

Scenario:

1. After reviewing the framework presented, consider yourself working on an active highway construction project. Imagine you discovered something wrong with the steel rebars. You've noticed a conflict between steel rebar and HVAC systems on site. It appears that the HVAC systems will be able to be installed, but only if the steel rebars are cut. You need to consult with the structural engineer to determine if this is structurally feasible.

It's 11:45 AM in July and the project is located in Las Vegas, NV.

1.1. Do you think using AR in this situation could be beneficial? YES / NO

1.2. Based on the framework and the scenario mentioned, which form of AR do you think would work best? Cellphones/tablets or Trimble XR10 or None

1.3. Explain your choice of device.

2. Changing the scenarios mentioned before:

After reviewing the framework presented, consider yourself working on an active highway construction project. Imagine you discovered something wrong with the steel rebars. You've noticed a conflict between steel rebar and HVAC systems on site. It appears that the HVAC systems will be able to be installed, but only if the steel rebars are cut. You need to consult with the structural engineer to determine if this is structurally feasible.

11:45 AM in December, the project is located in Las Vegas, NV.

2.1. Do you think using AR in this updated situation could be beneficial? YES / NO

2.2. Based on the framework and the changes applied to the mentioned scenario, which form of AR do you think would work best? Cellphones/tablets or Trimble XR10 or None

2.3. Explain your choice of device.

3. Adding to the scenarios mentioned before:

After reviewing the framework presented, consider yourself working on an active highway construction project. Imagine you discovered something wrong with the steel rebars. You've noticed a conflict between steel rebar and HVAC systems on site. It appears that the HVAC systems will be able to be installed, but only if the steel rebars are cut. You need to consult with the structural engineer to determine if this is structurally feasible.

It’s 11:45 AM in December, the project is located in Las Vegas, NV.

And you forgot the shop drawings needed for your solution in your office which is 2 hours away.

3.1. Do you think using AR in this updated situation could be beneficial? YES / NO

3.2. Based on the framework and the changes applied to the mentioned scenario, which form of AR do you think would work best? Cellphones/tablets or Trimble XR10 or None

3.3. Explain your choice of device.

4. Adding to the scenarios mentioned before:

After reviewing the framework presented, consider yourself working on an active highway construction project. Imagine you discovered something wrong with the steel rebars. You've noticed a conflict between steel rebar and HVAC systems on site. It appears that the HVAC systems will be able to be installed, but only if the steel rebars are cut. You need to consult with the structural engineer to determine if this is structurally feasible.

It’s 11:45 AM in December, the project is located in Las Vegas, NV.

You forgot the shop drawings in your office which is 2 hours away.

In addition, some take-off measurements with both hands are needed.

4.1. Do you think using AR in this updated situation could be beneficial? YES / NO

4.2. Based on the framework and the changes applied to the mentioned scenario, which form of AR do you think would work best? Cellphones/tablets or Trimble XR10 or None

4.3. Do you have any concerns about the chosen device (Cellphones/tablets or Trimble XR10) for this use of AR? YES / NO

4.3.1. If so, what concerns do you have and how do you envision overcoming them?

4.3.2. If not, why do you believe the situation would not raise any concerns? State your opinion based on the listed factors in the framework for the described scenario.

5. Do you think that the organization of the factors between 3 sections (pre-conditions, site conditions, and specifications) helped you choose the adequate form of AR (Cellphones/tablets or Trimble XR10)? YES / NO

5.1. Explain your answer.

6. Do you think the factors presented in the framework include most of the critical factors that would be encountered? YES / NO

6.a What factors do you think are missing, and should be added?

7. Based on your experience in using AR, do you think that this framework effectively supports decision-making related to choosing if/when AR communication can help? Briefly explain your answer.

8. Do you think that this framework will influence decision-making regarding AR adoption at NDOT? Briefly explain your answer.

9. Do you have any other thoughts/comments related to this framework?

APPENDIX C

SURVEY QUESTIONS FOR USERS WITHOUT PREVIOUS EXPERIENCE - DELPHI PANEL ROUND 1

Scenario:

1. After reviewing the framework presented, consider yourself working on an active highway construction project. Imagine you discovered something wrong with the steel rebars. You've noticed a conflict between steel rebar and HVAC systems on site. It appears that the HVAC systems will be able to be installed, but only if the steel rebars are cut. You need to consult with the structural engineer to determine if this is structurally feasible.

It's 11:45 AM in July and the project is located in Las Vegas, NV.

1.1. Do you think using AR in this situation could be beneficial? YES / NO

1.2. Based on the framework and the scenario mentioned, which form of AR do you think would work best? Cellphones/tablets or Trimble XR10 or None

1.3. Explain your choice of device

2. Changing the scenarios mentioned before:

After reviewing the framework presented, consider yourself working on an active highway construction project. Imagine you discovered something wrong with the steel rebars. You've noticed a conflict between steel rebar and HVAC systems on site. It appears that the HVAC systems will be able to be installed, but only if the steel rebars are cut. You need to consult with the structural engineer to determine if this is structurally feasible.

11:45 AM in December, the project is located in Las Vegas, NV.

2.1. Do you think using AR in this updated situation could be beneficial? YES / NO

2.2. Based on the framework and the changes applied to the mentioned scenario, which form of AR do you think would work best? Cellphones/tablets or Trimble XR10 or None

2.3. Explain your choice of device

3. Adding to the scenarios mentioned before:

After reviewing the framework presented, consider yourself working on an active highway construction project. Imagine you discovered something wrong with the steel rebars. You've noticed a conflict between steel rebar and HVAC systems on site. It appears that the HVAC systems will be able to be installed, but only if the steel rebars are cut. You need to consult with the structural engineer to determine if this is structurally feasible.

It's 11:45 AM in December, the project is located in Las Vegas, NV.

And you forgot the shop drawings needed for your solution in your office which is 2 hours away.

3.1. Do you think using AR in this updated situation could be beneficial? YES / NO

3.2. Based on the framework and the changes applied to the mentioned scenario, which form of AR do you think would work best? Cellphones/tablets or Trimble XR10 or None

3.3. Explain your choice of device

4. Adding to the scenarios mentioned before:

After reviewing the framework presented, consider yourself working on an active highway construction project. Imagine you discovered something wrong with the steel rebars. You've noticed a conflict between steel rebar and HVAC systems on site. It appears that the HVAC systems will be able to be installed, but only if the steel rebars are cut. You need to consult with the structural engineer to determine if this is structurally feasible.

It’s 11:45 AM in December, the project is located in Las Vegas, NV.

You forgot the shop drawings in your office which is 2 hours away.

In addition, some take-off measurements with both hands are needed.

4.1. Do you think using AR in this updated situation could be beneficial? YES / NO

4.2. Based on the framework and the changes applied to the mentioned scenario, which form of AR do you think would work best? Cellphones/tablets or Trimble XR10 or None

4.3. Do you have any concerns about the chosen device (Cellphones/tablets or Trimble XR10) for this use of AR? YES / NO

4.3.1. If so, what concerns do you have and how do you envision overcoming them?

4.3.2. If not, why do you believe the situation would not raise any concerns? State your opinion based on the listed factors in the framework for the described scenario.

5. Do you think that the organization of the factors between 3 sections (pre-conditions, site conditions, and specifications) helped you choose the adequate form of AR (Cellphones/tablets or Trimble XR10)?

5.1. Explain your answer.

6. Do you think that this framework effectively supports the decision-making related to when AR communication supports project teams? Briefly explain your answer.

7. Do you have any other thoughts/comments related to this framework?

APPENDIX D

GROUP DISCUSSION QUESTIONS – DELPHI PANEL ROUND 2

2. In your opinion what are the strongest elements of the framework?

3. In your opinion what are the weakest elements of the framework?

4. What aspect of the framework you would like to change to make it more usable?

5. Would you change anything in the organization of the factors in the framework?

6. For the group with previous experience:

5.1. What factors you would like to add to make it more effective in supporting decision-making?

5.2. What factors in the framework would NOT be helpful to decision-making that should be removed?

7. For the group with no previous experience:

6.1. What factors mentioned in the framework that seems self-evident and obvious enough that we can remove them?

6.2. What intuitive factors are missing and need to be added to the framework?

8. Do you think that this framework will effectively support decision-making related to when AR communication will support project teams?

9. Do you have any other thoughts/comments on this framework?

APPENDIX E

IRB APPROVED DOCUMENT

EXEMPTION GRANTED

Steven Ayer
SEBE: Sustainable Engineering and the Built Environment, School of
-
Steven.Ayer@asu.edu

Dear Steven Ayer:

On 2/4/2020 the ASU IRB reviewed the following protocol:

Type of Review:	Initial Study
Title:	Augmented Reality for contextually relevant communication in the construction industry
Investigator:	Steven Ayer
IRB ID:	STUDY00011449
Funding:	Name: Nevada Department of Transportation, Grant Office ID: FP00020779
Grant Title:	FP00020779;
Grant ID:	FP00020779;
Documents Reviewed:	• Consent Form, Category: Consent Form; • Grant Proposal, Category: Sponsor Attachment; • IRB Protocol, Category: IRB Protocol; • Supporting documents_31.01.2020.pdf, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions); • Wizard Submission Attempt, Category: Other;

The IRB determined that the protocol is considered exempt pursuant to Federal Regulations 45CFR46 on 2/4/2020.

In conducting this protocol you are required to follow the requirements listed in the INVESTIGATOR MANUAL (HRP-103).

Sincerely,

APPENDIX F

STATEMENT REGARDING CO-AUTHORS PERMISSIONS

I, Rita El Kassis, currently engaged in the final stages of my dissertation at Arizona State University, hereby confirm that I have duly obtained all requisite permissions from my co-authors of the journal articles incorporated into my dissertation's chapters. These permissions are pertinent to the inclusion of previously published or presentable materials, in which I hold the position of the first listed co-author, as stipulated by the regulations set forth by the Graduate College.

Each of my co-authors has been meticulously briefed about the purpose and context underlying the integration of their respective works into my comprehensive culmination document. They have explicitly granted their consent for their intellectual contributions to be employed for this specific objective and have unequivocally provided their authorization.

I recognize that this statement stands as a testament to the genuine and transparent process of acquiring permissions. I am fully aware that making any false assertions in this regard could lead to severe academic and legal ramifications. This affirmation is made in utmost good faith, aligning with my unwavering dedication to upholding academic honesty and with the utmost concern for the Graduate College and the broader academic community's welfare.

Rita El Kassis

Student ID: 1219051548

Date: September 28th, 2023