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Safety Challenges and Limitations in Augmented Reality Environments: A Review

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Construction sites pose multiple safety risks and hazards for workers. Augmented Reality (AR) has the potential to enhance safety on construction sites by providing real-time information, visualization, and training. For instance, AR can be used to train workers by simulating safety scenarios, allowing them to learn about potential hazards and safety protocols before starting work. AR helmets or glasses can display safety checklists and reminders, ensuring workers adhere to safety protocols. In addition, AR glasses can provide workers with real-time guidance in hazardous situations, including helping to track tools, equipment, and materials on the construction site, thereby reducing the risk of accidents. However, the implementation of AR in construction safety comes with certain obstacles that need to be addressed, ranging from worker distraction due to AR overlays to a limited field of vision when wearing AR devices to discomfort and fatigue. Thus, the aim of this study is to provide an overview of the key findings regarding the safety challenges and limitations associated with using AR technologies, as well as the type of technology used. The methodology used in this paper was a qualitative content analysis, a research method that involves systematically analyzing the content of technical research articles to identify patterns, themes, and meanings. The findings suggest that prolonged exposure to AR can lead to physical symptoms such as eye strain, nausea, and headaches, including spatial disorientation. Additionally, the technical limitations of these technologies, such as restricted vision and connectivity, can contribute to user discomfort. The paper highlights the importance of addressing these challenges to ensure the safe and effective integration of AR technologies in various domains. Also, it outlines the potential for future research and development in the field of AR safety technologies in construction.

Keywords: Augmented Reality, Challenge, Limitation, Construction, Safety.

Introduction

The construction industry plays a crucial role in shaping the world by creating structures and infrastructure that meet society's needs. However, the construction industry, which is characterized by unsafe conditions in its workplaces, is known for its high rates of accidents. According to the Bureau of Labor Statistics, 5,486 fatal work injuries were recorded in the United States in 2022, in which construction and extraction occupations had the second most occupational deaths (1069) (BLS, 2022). Based on statistics, the construction industry experiences more accidents and fatalities than other sectors. While other industries have successfully utilized different technologies to address safety problems, construction sites have been slow to adopt new technologies that could significantly enhance worker safety (Rupasinghe & Panuwatwanich, 2020; Awolusi et al., 2024). Therefore, it is advisable to consider implementing emerging technologies to improve safety performance in construction sites, as they can

provide real-time monitoring, data-driven decision-making, and improved training capabilities (Mohd et al., 2020; Awolusi & Sulbaran, 2021; Esfahani et al., 2024). One such technology is Augmented reality (AR), which has demonstrated its potential to enhance safety on construction sites. AR integrates virtual and real worlds, enhancing reality by overlaying additional virtual information (Fuge et al., 2012; Oke & Arowoiya, 2022). Furthermore, AR-based training modules can immerse workers in realistic scenarios, enabling them to practice safety protocols without exposing them to actual hazards (Li et al., 2018; Kaplan et al., 2021). There are different AR devices in construction such as AR glasses, smartphones, tablets, and devices like the HoloLens facilitate AR implementation on construction sites. AR has the potential to revolutionize onsite construction by providing various applications, such as improving communication and collaboration, enhancing project monitoring and documentation, and reducing risks throughout the construction process (Sivanesan et al., 2021). AR can also superimpose digital information, such as safety warnings or equipment instructions, directly onto the user's field of view, increasing worker awareness and reducing the risk of accidents.

Despite the numerous benefits of AR, several safety challenges or limitations associated with its use have been reported (Li et al., 2018). This highlights the need to identify and address specific safety concerns to successfully implement AR in construction. Addressing risk factors such as the violation of safety rules is crucial to ensure the safe application of this technology. For instance, the examination of fall from height (FFH) literature emphasizes the role of technology in enhancing construction safety (Khan et al., 2023). Recognizing and mitigating these challenges or limitations will enable construction professionals to effectively leverage AR technology, improving worker safety and preventing accidents. The current literature lacks a consolidated analysis of safety-specific challenges in AR for construction. While existing studies highlight AR's benefits, such as its application in training and hazard identification, they often neglect the physiological and operational impacts of prolonged device use. Issues like physical strain, distractions caused by overlaid information, and usability challenges are particularly underexplored in the context of dynamic and hazardous construction environments.

The integration of AR into the construction industry offers significant potential for improving efficiency and safety. However, the rapid adoption of this technology has revealed certain challenges and risks that must be addressed to ensure its safe and effective use. Therefore, the aim is to provide an overview of the key findings regarding the safety challenges and limitations associated with using AR technologies, as well as the type of technology used. In particular, issues such as health challenges, technical challenges, and potential distractions with AR systems can lead to unsafe practices on-site. Without addressing these concerns, the full safety-enhancing potential of AR may not be realized.

Literature Review

AR has become a revolutionary technology with diverse applications across different industries. However, the rapid progress in AR technology has also brought new challenges and limitations (El Kassis et al., 2023; Li et al., 2018). The construction industry is a complex and hazardous environment that is prone to high levels of accidents. A number of factors, such as poor working conditions, lack of knowledge, and miscommunication, can contribute to these accidents. The primary causes of construction accidents include falls from heights, being struck by moving vehicles or falling objects, and getting trapped by collapsing or overturning structures (Zhou et al., 2012). However, the use of emerging technologies can significantly enhance safety management in the construction industry (Zhou et al., 2013).

Several studies have been conducted to investigate the potential use of AR technology in the construction industry. These research works have examined how AR can be utilized for particular purposes such as design review, information exchange methods, construction inspections, monitoring

applications, construction layout tasks, and visualizing construction activities (El Kassis et al., 2023). These applications demonstrate the capacity of AR to improve collaboration, streamline workflows, and enhance safety by providing real-time guidance and hazard detection.

In the realm of AR, a comprehensive understanding of its applications and challenges has been pursued through various studies. Chi et al. (2013) analyzed 101 research studies that focused on the use of AR in architecture, engineering, construction, and facility management (AEC/FM). El Asmar et al. (2021) further explored the advantages and limitations of AR technology in the construction industry, while Fenais et al. (2018) conducted meta-analyses and systematic reviews to highlight the current applications and challenges of AR.

Although AR has demonstrated its potential, its implementation in construction environments remains fraught with challenges. A critical issue is the lack of field studies addressing AR usage in uncontrolled, dynamic construction settings. Controlled studies dominate the literature, which limits insights into how AR performs in practical, high-risk environments (Chalhoub et al., 2021). Limitations in hardware and software can impact the effectiveness of AR applications. Specifically, the limitations of current AR tracking technologies, rendering software, and computing power have hindered the widespread adoption of AR on construction sites (Shafiq et al., 2021; Zoleykani et al., 2023)

One major challenge is internet connectivity, particularly in rural or remote construction sites where internet coverage is limited. Reliable connectivity is crucial for real-time AR functionality, yet it remains a significant obstacle in many locations (El Kassis et al., 2023). This highlights the need to address practical considerations to ensure the seamless integration of AR technology in different settings. Thus, the focus of this research is to identify safety challenges and limitations associated with the use of AR technologies, along with the types of technology used. As the field evolves, understanding and overcoming these challenges will be pivotal for unlocking the full potential of AR in construction applications.

Research Method

The research used content analysis to transform qualitative data into quantitative data, which is often used in grounded theorizing and case-based research to reduce interview data into meaningful categories (Reger & Kincaid, 2021). Qualitative analysis involves collecting and analyzing textual data to gain a deeper understanding of a phenomenon, group, or impact. This study followed three phases of qualitative content analysis to identify safety challenges, and the technologies used.
(see Figure 1).

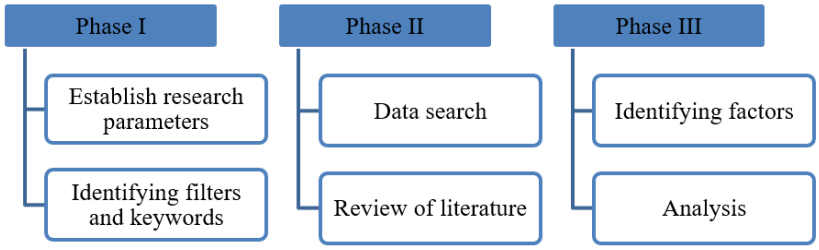

Figure 1. Phases of the Analysis Method for this Research

Phase I – Establish Research Parameters: The first step, identifying the unit of analysis, was the safety challenges of using AR technologies. The next step in this phase involved the selection of filters and keywords. The filters included the purposive selection of search platform, publication language

(English), the relevance of the document to the research (based on the review of the article), publication period (last ten years 2013-2023), and full-text availability to the research team. The Web of Science search platform was intentionally chosen because of its ability to provide a comprehensive review of peer-reviewed publications in the field and its capacity to connect with researchers. In the first stage, the research team identified five sets of keywords for the study (Table 1).

Table 1. Research Search Criteria

Search Set Number	Search Set Criteria
1	All fields: Safety; AND All Fields: Construction; AND All Fields: Augmented Reality; AND All Fields: Challenges
2	All fields: Safety; AND All Fields: Construction; AND All Fields: Augmented Reality; AND All Fields: Limitations
3	All fields: Safety; AND All Fields: Construction; AND All Fields: Augmented Reality; AND All Fields: Benefits

Phase II – Data Collection**:** The research team reviewed the literature based on the pre-established parameters (Phase I) and identified 106 peer-reviewed publications. The review of the compiled literature revealed that twenty research articles emerged in multiple search sets, and three of the articles were not accessible. So, the total number of identified publications using the three search sets was reduced to 83 (in Appendix A). Further filtering based on criteria such as publication language, relevance, and document accessibility led to a final set of 23 research articles, which were subsequently downloaded and analyzed.

Phase III – Data Analysis: The researchers conducted a demographic analysis of the shortlisted publications to help identify publication types, their published areas, publication trends (dates), and others. In addition, the researchers also conducted an analysis to identify the themes that emerged with safety challenges and technologies used. Some studies used experimental setups, such as controlled simulations, to evaluate the effectiveness of AR in enhancing safety and efficiency in construction. Others used qualitative methods, including case studies, interviews, and content analysis, to gather insights from construction professionals regarding AR applications. As well as a number of studies conducted systematic reviews and meta-analyses to synthesize existing findings on the technical and operational impacts of AR in the construction industry.

Findings and Discussion

Approximately 87% of the articles analyzed were journal articles, and 13% were peer-reviewed conference papers (Figure 2a). The research also found interesting trends over the years. Notably, there is a visible increase from 2020, peaking in 2022, as shown in Figure 2b. The increase in publication numbers over the past three years may be attributed to growing interest in the subject.

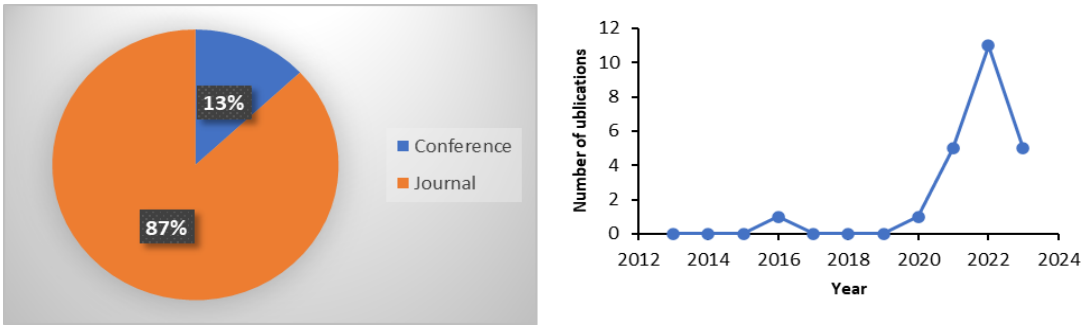

Figure 2. Publication (a) Type and (b) Number Per Year

Prolonged use of AR devices presents several safety challenges. To address these, researchers extract data from selected articles that highlight specific safety issues, such as motion sickness, physical strain, and mental health concerns. A statistical analysis is then conducted to determine the prevalence of these issues within the literature (Figure 3).

Motion sickness, characterized by symptoms like dizziness, nausea, and disorientation, is a common problem associated with AR and VR devices (Kiryu & So, 2007), affecting 53% of users. Extended use of these devices can also lead to physical strain, discomfort, and fatigue, with 26% of users reporting eyestrain and other adverse physiological reactions. Furthermore, the risk of physical harm increases, as users immersed in virtual environments may have limited awareness of their real surroundings, affecting 11% of users. Concerns regarding mental health are also significant, with 10% of users experiencing anxiety or related issues linked to technology use.

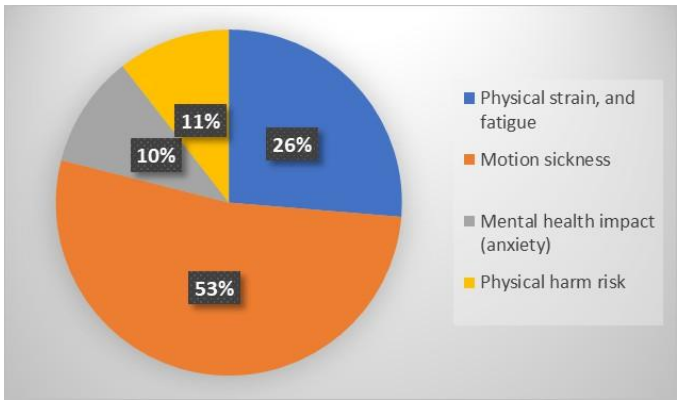

Figure 3. Physical and Health-Related Challenges

The percentages presented in Figure 4 were calculated after a thorough review of the research papers, offering insights into the technical and operational challenges linked to the implementation of AR technologies. The foremost challenge, accounting for 34%, is restricted vision. Restricted vision may pose obstacles to users, impacting their ability to navigate virtual environments seamlessly. Connectivity issues mentioned in 33% encompass unreliable internet connections that can hinder real-time functionality, affecting the overall user experience. Technical glitches, which account for 22%, represent potential hardware malfunctions or software errors that may disrupt the immersive experience. Safety concerns arise in active construction sites, where the use of AR devices could introduce tripping hazards and further restrict vision. Additionally, usability challenges, including complicated interface

manipulation and setup time requirements, contribute to the complexities associated with these technologies. Accessibility systems, with a rating of 11%, highlight the need for robust and user-friendly interfaces to ensure widespread adoption. Addressing these technical and operational challenges is crucial for the safe and successful integration of AR into various industries.

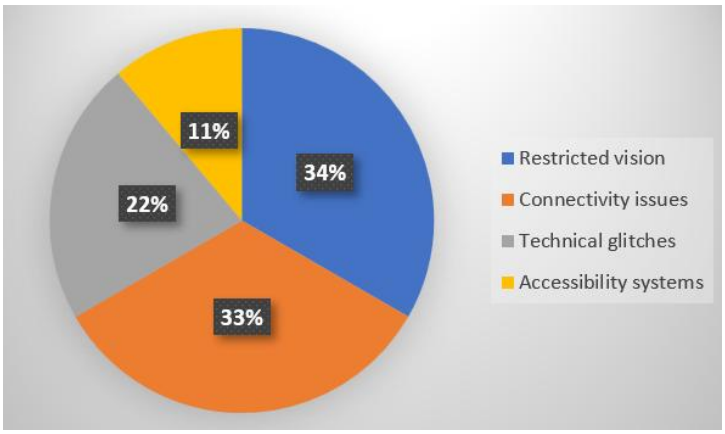

Figure 4. Technical and Operational Challenges

After conducting a comprehensive review of research papers, the percentages shown in Figure 5, were computed, offering valuable insights into the safety and distraction concerns associated with the integration of AR technologies across various contexts. The analysis revealed that 50% of distractions occur during immersive AR experiences, posing a risk by diverting users' attention from real-world hazards and potentially compromising safety. Additionally, there is a lack of consensus (on how to integrate raw data from multiple sources in real-time at the individual level during different operational tasks), accounting for 25%. Similarly, reduced spatial awareness (leading to an increased risk of collisions with physical objects or other workers on the construction site (Dobrucali et al., 2022), also at 25%, presents challenges in recognizing and addressing hazards within VR environments. These concerns also extend to workers using AR devices, where the immersive nature of the experiences may lead to reduced spatial awareness and increased risk of collisions. Addressing these safety and distraction concerns requires a holistic approach, including standardized safety protocols, comprehensive training programs, and consensus-building efforts to establish clear guidelines for the responsible use of AR technologies in various settings.

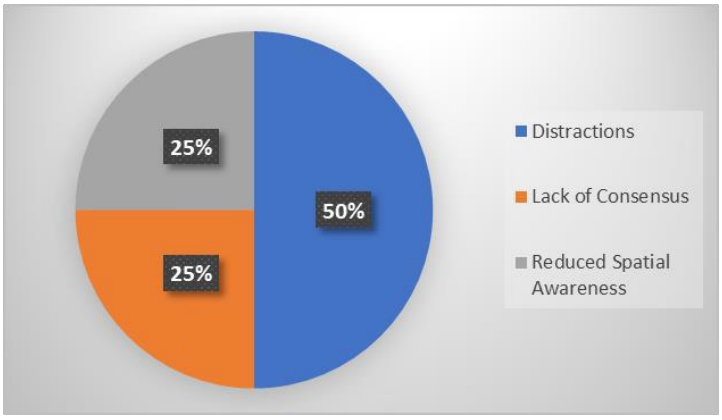

Figure 5. Safety and Distraction Concerns

The data provided reveals a significant emphasis on head-mounted devices and glasses in the context of technology usage, with 73%. These include various devices such as head-mounted displays, AR glasses, VR headsets, and AR headsets. Mobile Devices (Smartphones, Tablets) are 27%. This suggests a diverse technological landscape that involves both wearable head-mounted devices and more portable mobile devices, such as smartphones and tablets (Figure 6).

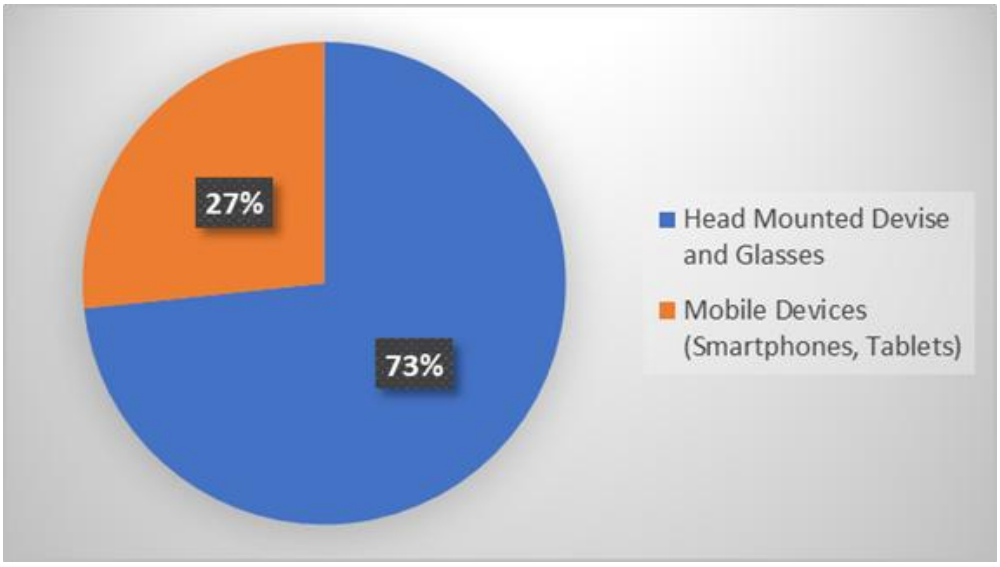

Figure 6. Technology Mentioned

Conclusion and Further Research

In summary, implementing AR technologies presents various difficulties in physical, health, technical, operational, safety, and distraction fields. Prolonged use of AR devices can have adverse impacts on both physical and mental health, leading to motion sickness and potential harm. As such, the well-being of the user should be of the utmost importance. Technical and operational challenges, such as connectivity issues, usability concerns, and learning curves, highlight the complexities of integrating AR into diverse applications. Safety concerns, including distractions, reduced spatial awareness, and a lack of consensus on how to integrate raw data from multiple sources in real-time at the individual level during different operational tasks, emphasize the need for careful consideration and standardization in the deployment of this technology. With the increasing adoption of AR, it has become crucial to address the challenges associated with it. It is essential to prioritize user safety while transforming AR technologies.

AR has made significant progress in improving visual enhancements and interactive experiences. However, there is often a lack of emphasis on the auditory aspects of AR. Most AR applications prioritize visual overlays and holographic displays, potentially overlooking the potential of a rich auditory experience. To create a more immersive environment for users, future work in AR should deliberately focus on enhancing the auditory dimension. Incorporating high-quality spatial audio, dynamic soundscapes, and interactive auditory elements can help researchers and developers create a more holistic and immersive experience for users. This multisensory approach aligns with the natural way humans perceive and interact with the world and can elevate the overall quality of AR experiences. Future AR developments can create a more immersive experience by addressing auditory aspects for seamless interaction with virtual elements.

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