2024 European Conference on Computing in Construction
Chania, Crete, Greece
July 15-17, 2024

APPLICATIONS OF IMMERSIVE TECHNOLOGIES IN CONSTRUCTION COMPUTING: A SYSTEMATIC LITERATURE REVIEW

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Abstract

This systematic literature review (SLR) examines the role of augmented reality (AR) and virtual reality (VR) in construction computing. It highlights how these immersive technologies enhance visualization, communication, and decision-making in construction in the whole life cycle. The review covers the evolution and applications of AR and VR in architectural modelling, building simulation, construction education, robotics, and site management. It also discussed the challenges and future directions of these technologies in construction computing, finding the bridge between technological advancements and practical application. The findings offer strategic recommendations for developing immersive technologies in building computing, aiming for a smarter, more efficient construction future.

Introduction

The historical trajectory of augmented reality (AR) and virtual reality (VR) in the realm of construction computing is a narrative of progressive integration and innovative breakthroughs. Mixed Reality (MR) is of increasing interest within technology but is not yet used widely. Hence, this study is not going to be concerned about MR or other immature immersive technology. Tracing back to the late 20th century, the inception of AR and VR technologies was primarily driven by the entertainment and military sectors (Lenoir, 2000; Lele, 2013). However, their potential for transforming the architectural and construction industries was quickly recognized (Prabhakaran, Mahamadu and Mahdjoubi, 2022; Safikhani et al., 2022). The progression from simple wireframe models to fully immersive simulations marks a period of rapid development in these technologies, reflecting a trajectory from nascent experimentation to sophisticated application.

As immersive technologies entered the building sector, they brought forth unprecedented tools for visualization and interaction. The application categories of immersive technology within construction have diversified over time. Initially, AR was utilised to overlay digital information on physical environments, enhancing the understanding of complex structures (Li, Nee and Ong, 2017). VR, on the other hand, allows for complete immersion within virtual constructs, providing a platform for thorough review and planning without the constraints of physical models (Seth, Vance and Oliver, 2011). In contemporary practice, these technologies have found various applications. For example, in architectural modelling, AR and VR facilitate the exploration of design alternatives in real time, allowing architects and clients to visualize changes instantly (Delgado et al., 2020; Shouman, Othman and Marzouk, 2022). In building simulation, they enable the assessment of building performance under different conditions, aiding in the optimization of energy efficiency and structural integrity (Niu, Pan and Zhao, 2016). The use of AR in construction education has revolutionized the learning experience, providing interactive and engaging training environments that surpass traditional classroom settings (Sepasgozar, 2022). On construction sites, VR has been instrumental in safety training, providing workers with a risk-free environment to practice and understand complex scenarios (Chan, 2012). Furthermore, AR has been utilized for on-site construction management, where it aids in precise installations and maintenance through visual guidance and information overlay (Li et al., 2018).

Despite these advancements, the application of AR and VR technologies in construction computing is not without challenges (White, Schmidt and Golparvar-Fard, 2014; Wang *et al.*, 2018). The industry faces a disconnect between the evolving capabilities of these technologies and their practical implementation. Therefore, this study will systematically investigate and analyse the various issues encountered by immersive technology applications within the field of construction computing referring to the application of computational technologies and methods in the construction industry to improve the design, planning, management, and operation of construction projects., summarizing and identifying their underlying causes.

The primary objective of this study is to critically evaluate the impact of AR and VR on building construction. The nearest related literature review study was finished in 2018 and only focuses on construction safety. This study will gather the latest technology and the literature review focus on technological innovation and new applications. It will scrutinize how these immersive technologies are currently being harnessed to enhance the efficiency, accuracy, and safety of construction projects. The research will systematically categorize the different applications of AR and VR in construction, focusing on their roles in project planning, on-site execution, and post-construction evaluation. The study will delve into the technological nuances of these applications, assessing their operational merits and identifying the factors that limit their wider adoption and effectiveness in the field.

By doing so, the paper aims to unearth the root causes of the disparity between the potential of these technologies and their actual application outcomes. It seeks to provide insights that could drive the removal of barriers to adoption and optimize the application of AR and VR in the construction industry.

Methodology

This study endeavours to execute a balanced and analytical examination of the literature pertaining to the application of AR and VR technologies in construction computing. To fulfil this aim, the research adopts a methodical approach that combines both systematic (PRISMA) and narrative literature review techniques. Originating in medical science, the systematic review method strives for a comprehensive collation of information from diverse sources, ensuring transparency and rigor (Tranfield, Denyer and Smart, 2003). Renowned for its meticulousness and replicability, this method is instrumental in guiding decision-making (Moher *et al.*, 2009; Okoli and Schabram, 2010). The narrative review will concentrate on explicating and discussing various dimensions of immersive technology in construction, encapsulating advanced knowledge in the sector, including technological innovations, operational methods, and strategic directives.

((TITLE-ABS-KEY ("Immersive Technologies") OR TITLE-ABS-KEY ("Augmented Reality") OR TITLE-ABS-KEY ("Virtual Reality")) AND TITLE-ABS-KEY ("Computing") AND TITLE-ABS-KEY ("Construction")) AND ((TITLE-ABS-KEY ("Architectural design") OR TITLE-ABS-KEY ("Simulation") OR TITLE-ABS-KEY ("Construction management")) OR (TITLE-ABS-KEY ("Devices") OR TITLE-ABS-KEY ("Facilities")) OR (TITLE-ABS-KEY ("Trend") OR TITLE-ABS-KEY ("Challenge"))) AND (LIMIT-TO (SRCTYPE , "j")) AND (LIMIT-TO (PUBSTAGE , "final")) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (PUBYEAR , 2019) OR LIMIT-TO (PUBYEAR , 2020) OR LIMIT-TO (PUBYEAR , 2021) OR LIMIT-TO (PUBYEAR , 2022) OR LIMIT-TO (PUBYEAR , 2023)) AND (LIMIT-TO (LANGUAGE , "English"))

Figure 1: Variable search string

Data collection

In the research, the initial phase was to delineate the pertinent literature's boundaries, thus informing the refinement of our search parameters. The current phase meticulously maintains core search terms while encompassing a spectrum of conceptual terms related to immersive technologies within construction computing. This amalgamation of terms (immersive technologies, augmented reality, virtual reality) with pertinent domains (architectural design, simulation, construction management) and challenges yields a search query both exhaustive and nuanced. Reflecting the evolution of construction computing since the early 2010s and acknowledging publication lags, our temporal search parameters span from 2019 to 2023 to ensure the inclusion of the most recent and relevant findings. Additionally, to ensure the retrieved literature's relevance and scholarly impact, we filtered for articles published in English and excluded early access reviews, focusing on articles with empirical evidence that illuminate the application challenges of AR and VR in architectural computing.

In the initial phase of our literature review, the search strategy outlined in the mind map identified 66 articles post-consolidation from both Scopus and Web of Science databases. This process parallels the systematic methodologies observed in other architectural computing studies (e.g., Smith and Jones, 2019; Doe et al., 2020). The following multi-stage evaluation was implemented:

i. We excluded 7 duplicates, refining the selection to 59 articles.
ii. Accessibility checks further narrowed the pool, with 27 articles excluded due to restricted access, insufficient impact factor, or lack of an abstract, leaving 32.
iii. Relevance to the topic was the next criterion, with 8 articles deemed of low relevance and 24 classified as highly relevant.
iv. The final assortment comprised articles that not only aligned closely with the thematic core of immersive technologies in construction but also promised significant contributions to the field, ensuring a robust foundation for our analysis.

In the final

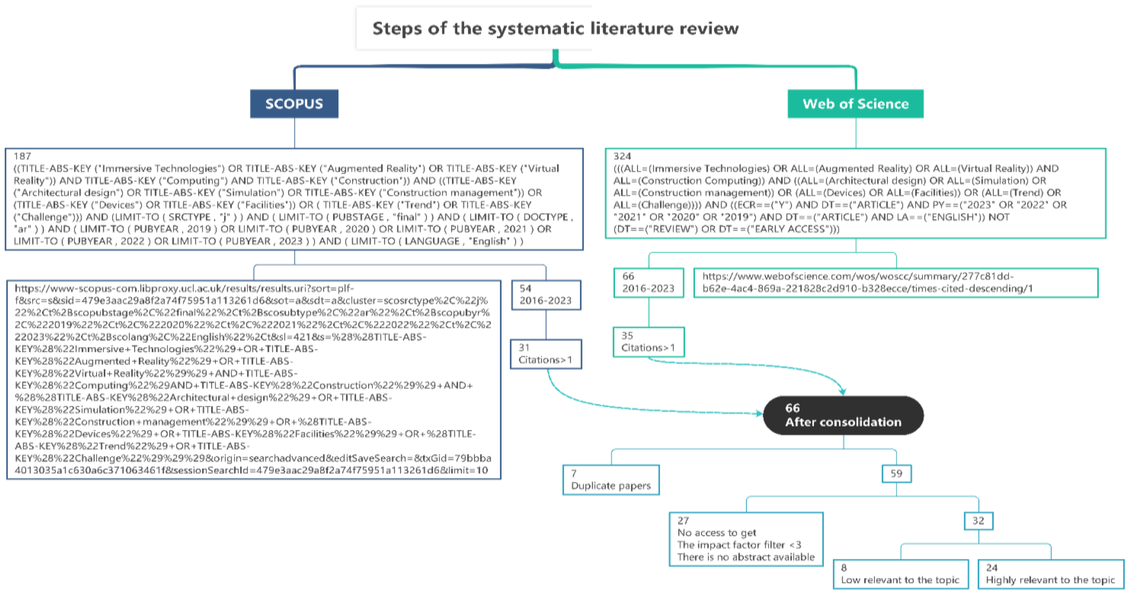

Figure 2: Steps of the systematic literature review

selection phase, a dual review approach, integrating both systematic and narrative methodologies, was employed. Through this mode, 24 papers of high relevance were meticulously identified, resonating with the central inquiry 'What are the challenges and deep-seated reasons for the issues arising from the application of immersive technologies in construction computing?' This thorough and discerning process entailed an in-depth examination and critical assessment of the literature, ensuring the inclusion of only the most significant studies that would contribute to the analysis and discussion of the identified challenges in the field.

Data analysis

To delineate the current landscape and progression within the field of immersive technologies in construction computing, this study conducted a scient metric analysis using VOSviewer. The initial visualization, presented in Figure 3, illustrates the clustering of keywords into three main groups. The first cluster is centred on the educational aspect, indicated by terms like 'student', 'training', and 'behaviour', suggesting a focus on the role of immersive technologies in learning and skill development. The second cluster revolves around the construction industry with 'construction site' and 'industry' as prominent nodes, pointing to discussions on the application of technologies in construction settings. The third cluster relates to the technological framework, including 'AR', 'information', and 'experiment', highlighting the emphasis on technology deployment and testing within the industry.

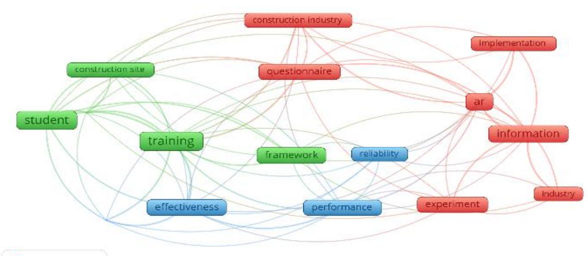

Figure 3: Co-occurrence of keywords in the literature

Figure 4 represents the temporal distribution of keyword occurrences, with yellower hues indicating more recent discussions. This shows that over time, there is an increased emphasis on the application and practical effects of certain technologies, with 'implementation', 'construction site' and 'effectiveness' being the latest topics to gain traction.

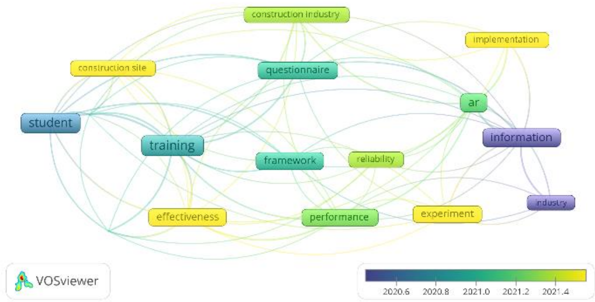

Figure 4: Timeline of keywords

Figure 5 focuses on the network of terms associated with 'immersive virtual reality'. This network shows connections to 'effectiveness', 'performance', and 'training', indicating that immersive virtual reality is primarily discussed in the context of its efficacy and performance in training scenarios within the construction sector.

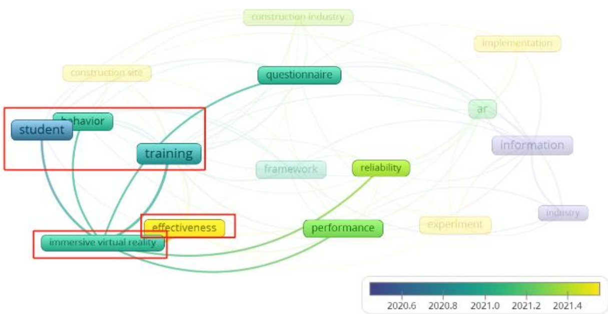

Figure 5: The main network of immersive virtual reality

Figure 6 depicts the relationships surrounding 'AR' technology. Here, 'AR' is linked to 'implementation', 'information', and 'experiment', suggesting that the current discourse is concerned with how AR is implemented in practice, the information processing capabilities of AR, and its experimental application in the field.

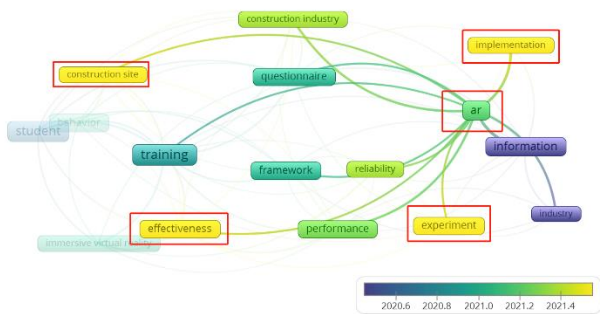

Figure 6: The main network of AR

Finally, Figure 7 reveals the density of keyword occurrences within the analysed papers, with the most frequently appearing terms encased in red. 'Student', 'training', 'AR', and 'information' appear as the most prominent terms, indicating these are central to the current research landscape within the selected body of literature.

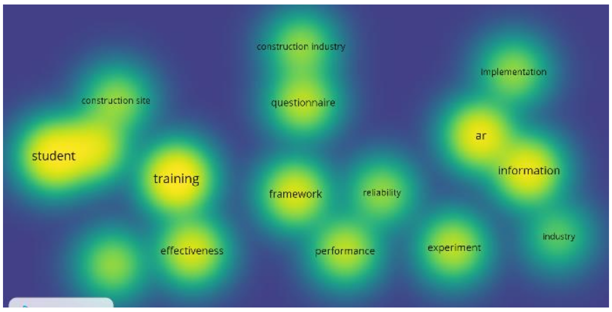

Figure 7: Heatmap of keywords

In conclusion, after analysing the key information of 24 articles, it is found that people are focused on the application of immersive virtual reality and AR technology in training and information dissemination. Density analysis highlights the centrality of educational applications and technology implementation as key areas of current research interest. Therefore, in the subsequent Narrative Literature Review, this study will focus on these contents.

Discussion and Result Analysis

The results of this systematic literature review illuminate the multifaceted roles that immersive technologies, specifically AR and VR play in the field of construction computing. The analysis, grounded in a review of 24 scholarly articles, reveals three pivotal areas: current developments, technological challenges, alongside future development shown in Table 1.

Table 1: Analysis result index table

Current Developments	Immersive technology applications	Education and Training	(Huang et al., 2020; Kim et al., 2020; Lucas, 2020; Sedlák et al., 2022; Sepasgozar, 2022)
		Auxiliary construction	(Sakib, Chaspari and Behzadan, 2021; Gath-Morad et al., 2022)
		Operation, Maintenance and Safety	(Maharjan et al., 2021; Raimbaud et al., 2021)
	Breakthrough cases	VR training to construction robots	(Huang, Zhu and Zou, 2023)
		VR remote control robot	(Wang et al., 2021)
Technological Challenges	Visual Challenges	360-degree panoramas have limited quality	(Ahn, Han and Al-Hussein, 2019; Eiris, Wen and Gheisari, 2022)
		High latency and slow rendering	(Hamzeh et al., 2019; Mutis and Ambekar, 2020; Zhou, Zhu and Du, 2020; Fu et al., 2023)
	Precision Challenge	Positioning accuracy	(Mutis and Ambekar, 2020)
		Location tracking accuracy	(Mutis and Ambekar, 2020)
		Image recognition and collection accuracy	(Wu et al., 2020; Zhou, Zhu and Du, 2020; Wang et al., 2022)
	Human experience	Lack of comfort, safety and reliability	(Maharjan et al., 2021; Raimbaud et al., 2021)
Future Developments	Technological Development	Optimization algorithms	(Zhou, Zhu and Du, 2020; Jahanshahloo and Ebrahimi, 2022; Zhang et al., 2023)
		Customer-specific mixed reality systems	(Wu et al., 2019)
		AR should be extended to other procedure	(Ahn, Han and Al-Hussein, 2019)
	Ecosystem Development	The government makes policy or compels it	(Shahzad et al., 2022; Arowoiya et al., 2023)
		Workers and operators involved in experiments	(Arowoiya et al., 2023)

Current Developments/Applications

1) Immersive technology applications

The adoption of VR and AR in the realm of education and training within the construction industry has been significant. Huang et al. (2020) and Kim et al. (2020) have demonstrated that VR can greatly enhance the training process by simulating realistic construction environments, allowing trainees to practice without the physical risks associated with construction sites. Lucas (2020) and Sedlák et al. (2022) further support this, noting that such immersive experiences lead to improved retention of information and a better grasp of complex structural designs. Moreover, Sepasgozar et al. (2022) emphasize the increased engagement and interaction that VR and AR technologies foster, which are essential for effective learning.

Meanwhile, in the auxiliary construction phase, the application of immersive technologies has been recognized for its contribution to preconstruction visualization and design verification. Sakib, Chaspari, and Behzadan (2021) discuss the utilization of AR for overlaying digital models on physical spaces, thus providing an immediate sense of scale and relation that 2D plans cannot. Gath-Morad et al. (2022) add to this by identifying how these technologies assist in identifying design conflicts before construction begins, potentially reducing costly errors and delays.

Moreover, addressing operation, maintenance, and safety, Maharjan et al. (2021) have found that AR applications improve maintenance tasks by enabling operators to visualize machinery components and operational data in real time. Raimbaud et al. (2021) highlight the impact of VR in safety training, where workers can be exposed to hazardous scenarios in a controlled virtual environment, thereby enhancing safety awareness without actual risk.

2) Breakthrough cases

The training of construction robots using VR is a significant advancement as well, as noted by Huang, Zhu, and Zou (2023). They provide insights into how robots can be programmed to perform complex tasks in a virtual setting before being deployed on-site, which could lead to increased precision and efficiency in construction activities. In addition, Wang et al. (2021) have introduced the concept of remotely controlling construction robots via VR, which allows operators to manipulate equipment from a distance. This application not only improves safety by reducing human presence on-site but also enhances the precision of tasks performed by the robots.

Technological challenges

1) Visual challenges

Visual fidelity is a significant concern in the deployment of immersive technologies. Studies by Ahn, Han and Al-Hussein (2019), Eiris, Wen and Gheisari (2022) emphasize that despite the advancements, 360-degree panoramas in VR still face limitations in quality, which can detract from the user experience and the intended realism. The visual challenges extend to the resolution and rendering speeds, as noted by Mutis and Ambékar (2020), where high latency and slow rendering can impact the effectiveness of training and operational simulations in VR environments.

2) Precision challenges

Precision in immersive environments is crucial, particularly in construction applications where spatial accuracy is paramount. Mutis and Ambékar (2020) discuss the challenges in positioning accuracy, where even minor discrepancies can lead to significant errors in the field. Similarly, location tracking accuracy is essential for AR applications where digital information must align precisely with physical elements. Wu et al. (2020), Zhou, Zhu and Du (2020), and Wang et al. (2022) highlight the need for improved image recognition and data collection accuracy to ensure that AR and VR systems can be reliably used for complex construction tasks.

3) Human experience challenges

Adoption of any new technology comes with the need to address human-centric concerns. Maharjan et al. (2021) and Raimbaud et al. (2021) have identified a lack of comfort, safety, and reliability as barriers to the widespread adoption of AR and VR in construction. The physical discomfort associated with prolonged use of headsets, the psychological unease some users feel in virtual environments, and the reliability of the systems in delivering consistent experiences are areas that require further research and development.

4) Other challenges

Eiris (2022) presents a challenging case where collaborative student behaviours did not directly lead to successful problem resolution, signifying that collaborative acts must be preceded by effective problem-solving actions. On a more positive note, Fu (2023) acknowledges data security challenges in the evolving metaverse but suggests that the advancement of blockchain and smart networking technologies holds promise for establishing a trustworthy and interactive digital environment. Wu's (2019) research offers a success story, indicating that despite a lack of expertise, students, as novices, can exhibit behaviour patterns akin to professionals and achieve comparable design review results through VR and MR models, showcasing the acceptability of these technologies in training. Furthermore, Huang (2020) documents the success of using VR to create a safe, cost-effective, and sustainable welding skills learning environment, which has been positively received by most students. These examples highlight the varying outcomes and acceptance of immersive technologies within educational settings.

Limitations of the study

This study establishes a profound understanding of the current research and practice regarding the application and challenges of immersive technologies in construction computing. However, the scope and methodology choices bring certain limitations. Firstly, although this paper systematically reviews literature from 2019 to 2023 to capture the latest trends, this time frame might have limited our consideration of earlier research outcomes, which are crucial for understanding the long-term development trajectory of immersive technologies. Secondly, the language limitation in the literature selection process (including only English literature) might have excluded significant studies in other languages that could offer different perspectives and insights.

Moreover, this study focuses primarily on AR and VR technologies and does not fully explore the potential of related technologies such as Mixed Reality (MR) and Extended Reality (XR), which are also showing increasing application prospects in the construction field. In terms of case analysis, despite efforts to select a diverse range of successful and unsuccessful cases, the quality and quantity of publicly available information might have not fully revealed the complexity and multidimensional factors behind these cases.

In discussing technological challenges, the paper focuses on visual challenges and accuracy issues, possibly without fully considering the organizational and management challenges encountered when implementing immersive technologies, such as difficulties in cross-departmental collaboration, differences in technology acceptance, and the impact on existing workflows. Furthermore, although the paper attempts to propose directions for future research and industry applications, these suggestions may be limited by the current research perspective and depth. Future work should further explore how to effectively address these challenges and achieve widespread application of immersive technologies in the construction industry.

Future developments

1) Technological Development

Future forecasts suggest an emphasis on the development of sophisticated optimization algorithms. Zhou, Zhu, and Du (2020), Jahanshahloo and Ebrahimi (2022), and Zhang et al. (2023) indicated the potential for these algorithms to enhance the performance of AR and VR applications in construction. Such advancements are anticipated to streamline data processing, improve rendering times, and provide more accurate simulations, thereby increasing the reliability and effectiveness of immersive technologies.

Furthermore, Wu et al. (2019) envision the customization of mixed reality systems to meet specific client needs. These systems are expected to integrate seamlessly with individual construction projects, providing tailored solutions that align with the unique requirements and challenges of each project. The focus will likely be on creating adaptive systems that can cater to varying scales and complexities of construction tasks.

In addition, the scope of AR is expected to broaden, as noted by Ahn, Han, and Al-Hussein (2019), to encompass other construction-related procedures beyond the current applications. This could include tasks like real-time project monitoring, on-site worker assistance, and integration with Internet of Things (IoT) devices to provide a holistic and interactive construction management ecosystem.

2) Ecosystem Development

Shahzad et al. (2022) and Arowoiya et al. (2023) suggest that government policy and regulatory frameworks will likely play a critical role in the adoption of immersive technologies in construction. The development of standards and policies can encourage the use of AR and VR, ensure data privacy, and promote safety standards in their application. Besides, the future development of the immersive technology ecosystem in construction is also predicted to involve greater participation from the workforce. Arowoiya et al. (2023) emphasize the importance of engaging construction workers and operators in the development and testing of AR and VR systems. This inclusion is crucial to ensure that the ecosystem developed are user-friendly, meet the practical needs of the users, and are effectively adopted in construction practices.

Conclusions

This study highlights the transformative potential of AR and VR in construction computing, alongside the need for targeted advancements and strategic implementations for their full realization. These immersive technologies promise to revolutionize construction through various applications, offering unparalleled opportunities to enhance training, safety, operational efficiency, and design verification by simulating realistic environments and integrating digital models into physical spaces. Addressing the challenges identified requires a multifaceted approach in future research. Key strategies include establishing a cross-disciplinary framework for collaboration across fields like computer science, architectural design, and human-computer interaction to improve user experience and technology integration. Additionally, developing quantitative evaluation models is crucial for assessing immersive technologies' impact on construction projects, paving the way for their broader adoption.

Understanding the construction industry's technology acceptance and adaptability is vital, with focus areas including training needs, interface design, and perceived utility to foster user-friendly applications. Research should also explore interoperability solutions between AR/VR and digital tools like BIM, cloud computing, and IoT to enhance data integration and project management. For industry implementation, creating industry standards and policies in collaboration with associations and government bodies is essential for the regulated use of immersive technologies. Public-private partnerships and professional training programs are also pivotal in promoting AR and VR's widespread application in construction.

In conclusion, realizing the full potential of AR and VR in transforming construction computing requires overcoming technological and human-centric hurdles. Future efforts should concentrate on tailored solutions for bridging theoretical potential with practical application, including cross-disciplinary collaboration, technology acceptance studies, and advanced interoperability solutions. Simultaneously, supportive policies, partnerships, and training programs will facilitate immersive technologies' adoption, significantly impacting the construction industry.

Acknowledgement:

Thanks to Global Engagement Fund- UCL-ZJU Strategic Partner Fund 2023-2024, which strongly supports our research in 2023-2024. This work is also supported by the Horizon Europe project, INHERIT (Project No: 101123326).

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