Virtual Reality and Augmented Reality Technology in Bridge Engineering: A Review

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ABSTRACT

Improving the quality of specialized disciplines within the construction sector is a necessary and inevitable trend. Each field has distinct characteristics, leading to differences in the adoption and application of technologies, which, in turn, drive tailored research approaches. Bridge construction, as a critical subdomain, frequently involves large-scale, complex projects that draw interdisciplinary attention from experts across various fields, extending beyond construction alone. This interdisciplinary nature underscores the importance of advanced technologies for management, design, construction, and communication, particularly in making specialized knowledge accessible and practical for diverse stakeholders. Virtual Reality (VR) and Augmented Reality (AR) have emerged as transformative tools to address these challenges. Despite extensive research on VR and AR in the broader construction industry, studies focused on their application in bridge construction remain limited. This paper consolidates existing research, examining VR and AR in the context of bridge construction. It provides a comprehensive overview of their benefits, challenges, equipment requirements, and emerging trends, providing insight to guide future research and support the practical implementation of VR and AR in this field.

Keywords-bridge engineering; virtual reality; augmented reality; construction technology; BIM

I. INTRODUCTION

The bridge construction industry consistently plays a vital role in the development of global infrastructure and economy. Bridges not only connect geographical areas but also facilitate the promotion of trade, tourism, and transportation. However, bridge construction demands a complex process spanning design, construction, monitoring, and maintenance. Strict technical requirements, intricate structures, and high safety standards pose ongoing challenges for engineers, managers, and the workforce within this sector [1].

In 2019, as the COVID-19 pandemic caused significant disruptions across various sectors, compelling schools, businesses, and construction projects to adapt their operations, Virtual Reality (VR) and Augmented Reality (AR) demonstrated their potential in remote simulation, training, and monitoring. Universities and educational institutions began implementing these technologies to provide students with realistic experiences in virtual environments, allowing them to continue their studies and research without the need for physical labs or actual construction sites [2]. In this context, the application of VR and AR in bridge construction has gained increasing attention [3]. VR and AR are utilized to simulate construction processes, monitor sites, and even facilitate remote meetings among engineers, contractors, and clients. VR allows engineers and designers to simulate construction sequences, inspect, and optimize designs in a virtual environment, minimizing risks and errors during actual construction while providing a platform to test innovative ideas before real-world implementation. With AR, engineers can overlay digital information directly onto the construction site, enabling more efficient and accurate project monitoring [4].

This study employed two Inclusion Criteria (IC) to identify studies related to the use of VR and AR in the construction sector, with a specific focus on bridge construction.

- IC1: Review of VR and AR technology in civil engineering.
- IC2: VR and AR technology in bridge construction.

Subsequently, the first 100 papers retrieved from Google Scholar using the above keywords, filtered by "sorted by relevance" and "review articles" were compiled. These papers were analyzed based on their abstracts and accompanying images to classify them into relevant fields and specializations. Summarized results are presented in Figures 1 and 2, with Table I showing highly cited and widely regarded studies.

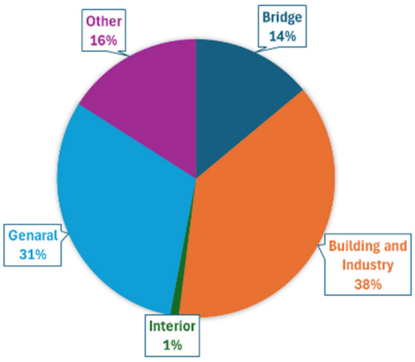


Fig. 1. An overview chart of research areas on VR and AR in the construction industry.

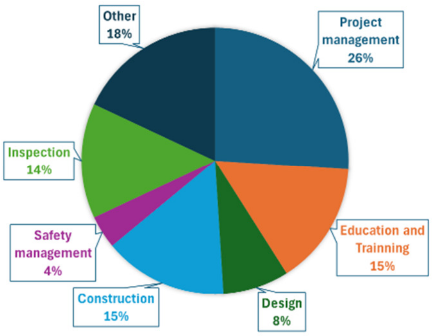


Fig. 2. An overview chart of research areas on VR and AR.

TABLE I. OVERVIEW OF NOTABLE STUDIES

Study	Approach	Technique	Specific
[5]	Investigated the potential of VR applications in pre-discharge processes to support home therapy, emphasizing how this technology can enhance the design and functionality of living spaces.	VR	Building, Design
[6]	Examined VR applications in the manufacturing industry, providing insights that can be directly applied to the construction sector.	VR	General, Project management
[7]	Highlighted the transformative role of VR in construction education and training, particularly in enhancing safety practices through immersive learning environments.	VR	Bridge, Education and Trainning
[8]	Explored how VR and AR can address challenges in construction management, including project planning, progress tracking, and quality management.	VR, AR	Building, Project management
[9]	Demonstrated how VR combined with BIM can generate real-time quantity takeoffs during the design phase, streamlining project workflows.	AR, BIM	Design, Building
[10]	Explored the challenges and opportunities of AR technology for field inspection applications.	AR	Inspection, Construction

The integration of VR and AR into the construction industry represents a transformative leap in enhancing project efficiency, quality, and safety. These technologies have proven invaluable in refining project management and augmenting the training and skill development of engineers and construction workers. Despite these advances, the specific application of VR and AR to bridge construction remains underexplored. This gap is particularly significant given the complex, large-scale nature of bridge projects, which present unique challenges not as prevalent in general building construction.

The bridge construction sector is distinct from other construction fields due to its engineering complexity and the critical safety implications of its structures. Existing VR and AR research predominantly addresses broader construction and architectural design, with extensive studies dedicated to building construction, project management, and educational applications. However, the unique demands of bridge construction, ranging from intricate load analyses to alignment with diverse environmental factors, require tailored VR and AR solutions that are currently lacking in depth and specificity in academic research.

Furthermore, the education and training of bridge engineers illustrate a crucial area where VR and AR could bridge the gap between theoretical knowledge and practical application. Traditional educational approaches in this field emphasize theoretical frameworks and simulated models, which often fail to provide the experiential learning necessary for understanding the multifaceted nature of real-world bridge construction. The introduction of VR and AR into educational settings could revolutionize this, offering students and young professionals hands-on experience without the logistical and financial constraints of physical models or on-site training.

Despite the clear benefits, the adoption of VR and AR in bridge construction faces several technical and implementation challenges. The complexity of bridge projects requires the development of specialized VR and AR tools that are robust enough to model large-scale infrastructures under varying environmental conditions.

This study aims to address these gaps by providing a comprehensive analysis of the current state of VR and AR technology in construction, with a particular focus on bridge projects. The following sections outline a framework for developing VR and AR applications tailored to bridge construction, proposing solutions to current technological limitations and suggesting directions for future research.

II. LITERATURE REVIEW

A. Overview of the Bridge Construction Industry

The design and construction of bridges have undergone a long and significant evolution from ancient times to the present day. Initially, the bridge design was based mainly on oral knowledge and practical experience. Engineers of the past often lacked formal drawings, relying solely on knowledge of materials and structural arrangements passed down through generations. During the Renaissance and the Industrial Revolution, the development of hand-drawn illustrations marked a crucial breakthrough in bridge engineering. Technical drawings, created manually with rulers and basic tools, allowed engineers to better visualize bridge structures before construction. The advent of Computer-Aided Design (CAD) in 1963 ushered in a new era [11], as it allowed engineers to produce highly accurate digital drawings while significantly reducing time and effort compared to hand drawing. With its quick computational abilities and digital data storage, CAD became an indispensable tool in modern bridge design. In the 1970s, 3D CAD was first introduced, but it was not until the late 1990s, with the advent of AutoCAD 3D, that 3D design became widespread [12]. Today, 3D drawings are the standard in bridge construction, offering precise simulation of structures in three-dimensional space. This enables engineers and architects to verify technical specifications and visualize the entire project in detail before construction. Especially with the power of today's computer components, new technologies such as VR and AR are being researched, developed, and applied in design and construction processes (Figure 3). VR enables engineers to "step into" a virtual bridge model to inspect and adjust design details within a three-dimensional space, while AR can support monitoring and construction processes by overlaying virtual information onto the real environment [13]. In the future, experts predict that bridge design may fully transition into a virtual environment, where engineers can collaborate remotely in a shared space to design, simulate, and even test bridges before actual construction begins.

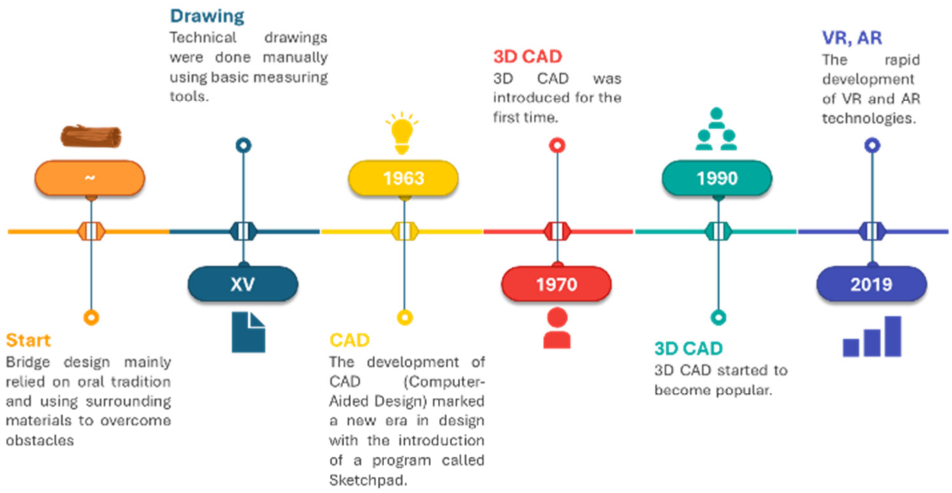


Fig. 3. Timeline of VR and AR development in construction engineering.

In construction engineering, structures can be divided into various domains based on specific technical factors. To ensure safety, efficiency, and durability, the construction sector has been divided into two main specialized fields: bridge engineering and civil and industrial building engineering. Consequently, design standards are also issued separately for these specializations to optimize structural performance. For example, in the United States, the AASHTO LRFD Bridge Design Specifications [14] are used for bridge construction, while AISC 360 [15] serves as the standard for steel structures in residential and civil buildings. In Europe, the Eurocode-8 [16] standards for calculating seismic impacts are also divided into two distinct parts: Part 1 for buildings and Part 2 for bridges. Some specific characteristics of the bridge construction industry include the following:

- Load-bearing requirements: In addition to static loads, bridge structures endure numerous dynamic loads, especially from traffic crossing the bridge. These forces are often random, non-static, and lack a fixed pattern. Therefore, to ensure safety, these forces are combined into large loads in design. Due to these load-bearing demands, bridge load-bearing structures are also complex, posing design challenges. This is especially evident in concrete bridges, where load-bearing beams are typically much larger than in buildings. Although load-bearing structures may lack distinctive aesthetics or architectural highlights, they require intricate reinforcement layouts and specialized construction methods to handle substantial load combinations. Consequently, bridge structures are often large, dense, and robust.
- Geological and environmental conditions: Bridge construction projects typically cover extensive areas and, unlike buildings, may extend over several kilometers, resulting in varying geology and environment across each abutment. Additionally, bridges often span structures that connect two points over challenging terrain, such as deep rivers or ravines, making exploration, surveying, and inspection difficult.

Bridges are large structures designed to meet transportation needs, and in many places, they are considered city landmarks, such as the Golden Gate in San Francisco (USA) and the Dragon Bridge in Da Nang (Vietnam). These projects require substantial financial investment and extended construction time. Thus, they demand strict management of finances, material resources, construction techniques, safety protocols, and maintenance inspections due to their large scale and challenging site accessibility.

B. Benefits of VR and AR in Bridge Construction

The close integration of VR and AR brings exceptional advantages, from design visualization to improved collaboration and workplace safety. Instead of merely looking at traditional 2D drawings, engineers can now step into a virtual bridge environment and explore every structural detail before construction begins. This not only enables them to detect design flaws easily but also optimizes the construction process, saving time and costs. For critical structures such as bridges, VR and AR provide a powerful solution for risk mitigation. From training personnel in safe simulated environments to supporting post-completion maintenance inspections, these technologies are effectively helping the bridge construction industry achieve high efficiency.

1) Design Visualization and Simulation

VR and AR enable engineers to visualize the structure in a 3D space before construction, facilitating feasibility checks, detecting design flaws, and making quick adjustments. This is especially important for complex bridge projects with multiple technical and structural components. VR allows users to view a 3D model of the bridge before construction, enabling feasibility assessments of design options and rapid error detection. In [17], it was highlighted that VR enables construction engineers to examine bridge structural details, such as beams, cables, and piers, to assess load-bearing capacity and durability under various load conditions. AR also provides practical solutions for on-site progress inspection.

2) Enhanced Collaboration and Communication

Integration of VR/AR in project management not only improves communication quality but also minimizes cost and time risks, as design or construction issues can be quickly identified and resolved before they impact the site. For large bridge projects that involve multiple stakeholders, these technologies enable teams at different locations to interact and discuss designs simultaneously, enhancing communication and collaboration between engineers, contractors, and clients.

3) Training and Skill Enhancement

VR/AR allows engineers and workers to train in a virtual and safe environment where they can recognize and practice complex tasks before working directly on-site. This helps reduce risks and enhances readiness for emergency situations in bridge construction, such as rescue operations during construction incidents.

4) Error Minimization and Process Optimization

AR can display 3D models and overlay information in the real environment, allowing engineers to inspect bridge structures with high precision, immediately identifying design errors or construction deviations. This minimizes construction errors, avoids post-completion repairs, and thereby increases efficiency and saves project time.

C. Challenges of VR and AR Technology in Bridge Construction

VR and AR have unlocked significant potential in construction, enhancing design, construction, and maintenance processes. However, the application of these technologies still faces numerous challenges and limitations.

1) High Initial Investment Cost

A significant challenge in using VR and AR in bridge construction is the high initial cost. Companies must invest heavily in hardware such as VR headsets (e.g., Oculus Rift, HTC Vive), controllers, 3D modeling software, and simulation systems. Although manageable for large projects, these expenses are prohibitive for smaller companies with limited budgets. Developing simulation content requires skilled engineers, complex software, and project-specific customizations, further raising costs. Additionally, maintaining and upgrading rapidly aging equipment and training staff adds to the financial burden. Despite these challenges, the long-term benefits of improved productivity, reduced delays, and better resource management make VR/AR a worthwhile investment in bridge construction.

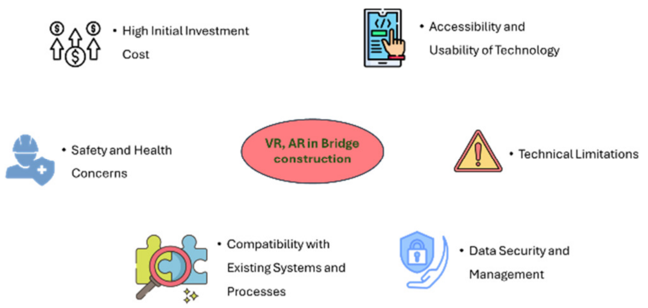


Fig. 4. Challenges of VR/AR in construction engineering.

2) Accessibility and Usability of Technology

Another significant challenge in implementing VR/AR in bridge construction is accessibility and usability. Companies need highly specialized personnel to develop and operate VR simulations, which require not only technical skills but also a deep understanding of bridge design and complex construction processes. Additionally, managing and operating these highly skilled personnel require managers also undergo formal training and possess a comprehensive knowledge of current technologies. Training engineers and workers to familiarize themselves with these technologies requires time and financial resources, an investment that not all companies can afford.

3) Technical Limitations

Although VR/AR technology is rapidly advancing, it still faces challenges in achieving high accuracy when simulating complex technical details in bridge structures. Specifically, bridge models with numerous details require large amounts of data and computational capacity, which can strain hardware processing power, potentially resulting in missing details during rendering. Current VR/AR devices have limited processing capabilities when handling large and complex models, leading to lag or missing details in the simulation.

4) Compatibility with Existing Systems and Processes

Many construction companies have already implemented traditional design and management software. Integrating VR and AR into existing processes can be challenging due to incompatibility with legacy systems, often requiring complete system upgrades or replacements. Additionally, the lack of standardized guidelines for managing this technology in construction poses difficulties for effective implementation.

5) Safety and Health Concerns

A critical challenge when applying VR in construction environments is the safety and health of users. Prolonged VR use may cause symptoms such as visual fatigue, dizziness, and loss of balance among workers and engineers. These effects not only reduce work performance but also pose hazards, especially in construction settings that require high concentration and absolute safety.

6) Data Security and Management

The use of VR and AR in construction can generate substantial amounts of project data, which requires robust security systems to protect information from cybersecurity threats. Data security and privacy issues must also be carefully considered.

The future of bridge construction is poised to be revolutionized by advances in VR and AR. Predictions suggest that these tools will become more sophisticated, with enhanced realism in VR simulations allowing for more detailed and comprehensive design testing under varied environmental conditions. AR is expected to improve in providing real-time, on-site overlays of construction plans and structural analyses, thereby increasing precision and safety during the construction phase. Integration with other digital tools such as Building Information Modeling (BIM) and Artificial Intelligence (AI) is likely to deepen, enabling more efficient and informed decision-making processes. These technological developments are anticipated to not only streamline construction practices but also transform training and maintenance protocols, making the bridge construction industry more efficient, safe, and adaptable to future challenges.

Despite promising advances in VR and AR technologies for bridge construction, several research gaps remain. Integration with existing systems, real-time data processing, and user training for effective technology adoption are underexplored. There is also a need for detailed economic analyses to understand the cost-effectiveness of these technologies. Furthermore, studies on the use of VR and AR for the maintenance, monitoring, and enhancement of safety and risk management in bridge construction are sparse. Addressing these gaps could significantly improve the efficacy, safety, and cost-efficiency of bridge construction projects.

D. Equipment

In a VR world, equipment plays an essential and irreplaceable role. Currently, there are two popular options on the market: 3-DOF and 6-DOF device sets:

- 3-DOF device sets use smartphones as the screen mounted on a headset.
- 6-DOF device sets involve a headset connected to a computer, including HTC Vive, Oculus Rift, and Oculus Quest 2.

VR and AR devices represent a promising market segment for electronics companies, as demonstrated by the diversity of providers. VR/AR devices such as Microsoft HoloLens 2, Magic Leap 2, Oculus Quest 2, and HTC Vive Pro 2 are offered by major corporations, delivering breakthrough solutions in user experience visualization. Most devices are designed primarily to support visual perception. Beyond these devices, AR technology can now also be used directly on personal mobile devices, such as smartphones and tablets, making it accessible and familiar to all users. Additionally, creating a vivid and interactive VR experience depends not only on hardware specifications but also on the critical role of software and the expertise of developers. Dedicated software tools, such as Unity, provide powerful capabilities for VR/AR development but require user proficiency and robust hardware to function effectively. Most of the current software offerings are commercial products. However, some, such as Unity and Unreal Engine, provide various options, including free versions with basic features, as well as commercial options, such as Unity Pro, for product commercialization. In contrast, software such as Blender is entirely free and open source.

For bridge construction simulation software today, we suggest the following key components for a computer capable of designing VR and AR models:

- CPU: Intel Core i5 12400 or higher,
- GPU: RTX 3060 or higher,
- RAM: DDR4, 32GB or higher.

This is the minimum configuration, designed to allow for scalability while ensuring compatibility with hardware-demanding software. This setup delivers robust performance for rendering and simulation tasks without requiring the high costs associated with premium components.

III. GENERAL PROCESS

Applying VR and AR technology in bridge construction requires a detailed and well-structured process, from the initial design phase to the implementation of the virtual model, creation of interactions, and post-construction monitoring and maintenance. In [18], a VR construction process was proposed for projects using BIM technology, consisting of four main steps (Figure 5).

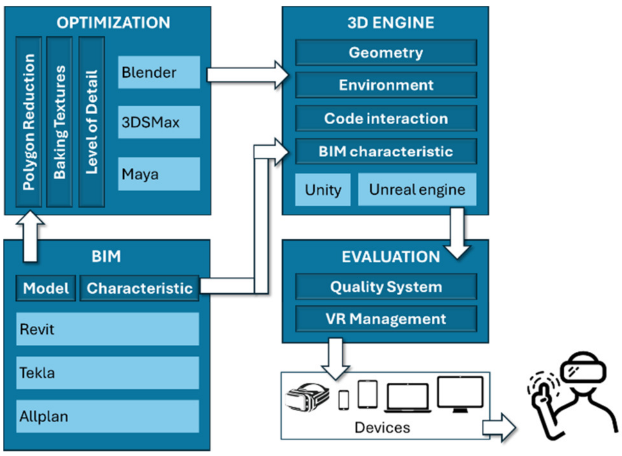


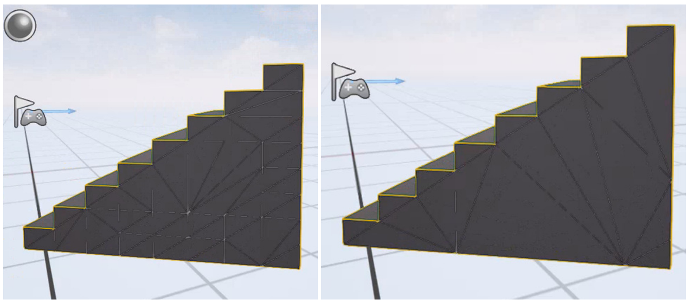
Fig. 5. General process.

A. Create the Initial Design Model Using CAD/BIM Software

The first step is to generate 2D technical drawings and a 3D model of the bridge using BIM design software such as AutoCAD and Revit. In this phase, engineers detail the dimensions, shape, structure, and key technical elements of the bridge. The BIM model allows for the integration of extensive technical information into a detailed 3D representation of the bridge. This includes not only basic specifications but also data on construction materials, timelines, costs, and other factors. BIM allows the effective management of information related to each bridge component, from materials to construction processes.

B. Optimize the Model with 3D Modeling Software

This step is crucial to ensure the model runs smoothly in AR/VR environments. The 3D model in BIM often contains a large number of polygons, especially in detailed components. A high polygon count can make the model too heavy to handle in AR/VR environments [11]. Optimization focuses on reducing polygon count and adjusting model resolution without losing essential details, thereby enhancing processing performance while maintaining realism (Figure 6.). This can be achieved using specialized 3D modeling applications such as Blender, 3DS Max, or Maya.



(a) (b)

Fig. 6. Optimization by polygons' reduction: (a) high polygon count, (b) low polygon count.

The optimization process must be handled carefully to avoid losing small yet essential details in the entire model, especially critical components such as bearing stones, reinforcing bars, chamfered beam sections, and other key structural elements.

C. Use 3D Game Engines

A game engine, such as Unity or Unreal Engine, is essential in developing AR/VR applications, as these platforms provide the necessary tools to create and manage virtual environments. Safety protocols can also be incorporated from a database.

- Unity and Unreal Engine support the creation of highly detailed 3D environments. The optimized BIM model is imported into these engines to create a virtual bridge or construction project.
- The real-world terrain of the construction site can be simulated using detailed terrain data or point cloud maps collected from 3D scanning technologies or drones. This approach ensures a more accurate and realistic environment in virtual space.
- Realistic movements, a core feature of Unity and Unreal Engine, can be added to visualize on-site activities interactively.

D. Real-Time Interaction and Adjustment

After models and movements are created, Unity and Unreal Engine enable direct real-time interaction. Users can observe and perform actions, such as navigating the simulated space, changing object positions, and examining different scenarios on the construction site. This interactivity allows engineers to analyze and assess construction processes and make timely adjustments. Visualizing construction activities and processes in a virtual environment saves time and minimizes risk.

E. Run the AR/VR Application with the Converted BIM Model

Finally, after completing the optimization and development steps, the AR/VR application must ensure smooth performance and interactivity with the converted BIM model. Software like Unity and Unreal Engine offers options to deploy the application on virtual or augmented reality devices, enabling users to interact with the model in real space.

IV. TRENDING

VR and AR technologies are increasingly recognized as transformative forces within the construction industry, especially in bridge construction, which requires rigorous management, adherence to high safety standards, and complex technical solutions. Despite their promising applications, VR and AR face substantial challenges in widespread adoption. These include high implementation costs, the need for specialized training, and the integration of these technologies into existing workflows without disrupting established processes. Moreover, current technological limitations, such as data accuracy and real-time processing capabilities, also pose significant hurdles. Looking to the future, a vision emerges in which VR and AR become integral components of bridge construction. This future is characterized by the seamless integration of digital and physical workspaces, allowing construction teams to work more efficiently and safely. Advanced VR and AR systems could provide real-time on-site support during construction, offering virtual overlays of structural models and highlighting potential safety issues before they become hazards. This integration also promises to connect with other technological trends in construction, such as the use of BIM and AI, creating a more interconnected and intelligent construction ecosystem.

A. Integration of VR/AR with BIM

A prominent future trend is the combination of VR, AR, and BIM in bridge design and construction processes. BIM technology has been widely used to manage data and information modeling in construction projects. Integrating VR/AR into BIM will allow engineers and architects to visualize bridge projects more realistically and in greater detail. In [19], AR was shown to effectively bridge the gap between digital BIM models and their real-world counterparts, enhancing the usability of digital designs on-site. The integration of AR also brings additional requirements for BIM models and tools, particularly concerning the fourth dimension of BIM (time). The study in [20] explored the use of VR to overcome communication and collaboration barriers across project phases. Other studies, such as [21], have also shown that integrating BIM with VR and AR generates discussions among design, management, and construction teams, leading to increased efficiency and productivity.

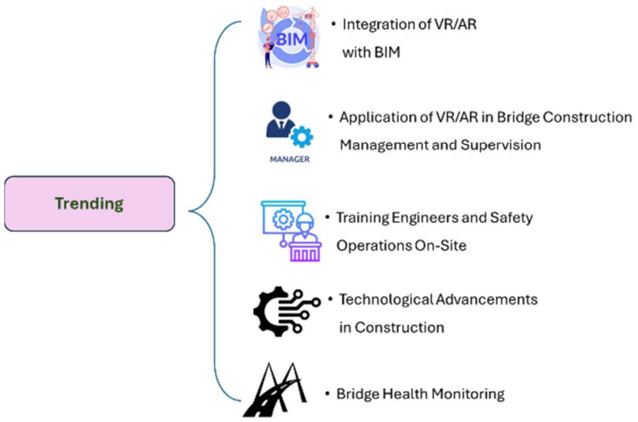


Fig. 7. Trends.

B. Application of VR/AR in Bridge Construction Management and Supervision

In recent years, the capabilities of VR and AR in construction management and supervision have been extensively researched, revealing their increasing effectiveness in large and complex projects. In [22], AR was used to overlay critical project data onto the real environment, enabling engineers to perform on-site inspections and make decisions more easily. Through virtual environments, construction steps are illustrated and potential scenarios are simulated, allowing workers and engineers to anticipate events and agree on safe construction methods.

C. Training Engineers and Safety Operations On-Site

VR/AR applications not only create a platform for design discussions and option selection but also provide an effective and safe way to train engineers. This is a prominent trend in education and training, particularly in bridge construction, which requires hands-on practice and real-world experience. Using VR and AR in training bridge engineers leverages visualization and user interaction capabilities. Virtual learning environments allow students and engineers to interact with complex bridge models, gaining a deeper understanding of construction and maintenance processes. VR and AR enhance learning experiences and practical application in construction, allowing students to engage in real-world scenarios without having to be on-site [7]. In [23], two simulation models of cantilever and incremental launching methods, common bridge construction techniques, were proposed, providing a direct perspective for teaching without requiring field visits.

D. Bridge Health Monitoring

VR and AR technologies are being developed to support bridge maintenance by enabling early detection of structural issues. VR can create virtual bridge models, allowing engineers to inspect components in detail without needing access to hazardous areas. AR provides a more intuitive approach, allowing engineers to assess the actual condition of the bridge through augmented images, making it easier to detect cracks or signs of damage. In [24], BIM was integrated with VR and AR, offering new opportunities to manage and display Structural Health Monitoring (SHM) data in a 3D environment, highlighting the significant potential in infrastructure monitoring applications.

E. Technological Advances in Construction

In [25], a 3D body and hand position tracking system was investigated, allowing the recording of movements and directions of construction workers. This real-time simulation system links remote worker movements to virtual robotic construction workers, simulating various construction scenarios. Additionally, potential research directions include modifying real-time models on-site to allow for efficient project planning and adjustments. With current IoT and telecommunications technology, remote control and operation through AR and VR also present promising ideas. For example, foundational studies like [26] explored virtual sensors within virtual environments and digital twins.

V. CONCLUSIONS

This paper synthesized various studies on the application of VR and AR technologies in the construction industry. An analysis of these studies reveals that most researchers focus on general construction practices and technical education. This paper distinguishes the specific characteristics of bridge construction compared to civil and industrial construction, highlighting the unique aspects of bridge engineering. Furthermore, benefits and challenges were identified in implementing VR and AR in bridge construction, a sector characterized by its complex and specialized requirements. The advancement of VR and AR technologies has made significant progress, enabling the simulation of large, intricate structures in difficult-to-access locations while also providing interactive virtual environments that enhance safety and improve training efficiency for engineers and workers.

This study also presents a comprehensive overview of popular VR and AR devices and outlines the hardware requirements necessary to establish a complete virtual environment. Based on existing research, a practical framework is proposed to apply VR and AR technologies in bridge engineering, offering detailed guidance for real-world implementation. Finally, emerging research trends and potential areas for development are highlighted, particularly the use of virtual monitoring technologies in construction projects. In conclusion, the paper offers a comprehensive and holistic overview of VR and AR applications in bridge construction, serving as a foundation for future research and practical deployment.

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REFERENCES

[1] U. Riedlinger *et al.*, "Digital Support for Bridge Inspectors through Mixed Reality BIM Data Visualizations," in *Computing in Civil Engineering 2021*, Orlando, FL, USA, May 2022, pp. 1359–1366, https://doi.org/10.1061/9780784483893.166.

[2] A. A. Eldokhny and A. M. Drwish, "Effectiveness of Augmented Reality in Online Distance Learning at the Time of the COVID-19 Pandemic," *International Journal of Emerging Technologies in Learning (iJET)*, vol. 16, no. 09, May 2021, Art. no. 198, https://doi.org/10.3991/ijet.v16i09.17895.

[3] B. Abbasnejad, S. Soltani, A. Karamoozian, and N. Gu, "A systematic literature review on the integration of Industry 4.0 technologies in sustainability improvement of transportation construction projects: state-of-the-art and future directions," *Smart and Sustainable Built Environment*, Aug. 2024, https://doi.org/10.1108/SASBE-11-2023-0335.

[4] J. M. Davila Delgado, L. Oyedele, T. Beach, and P. Demian, "Augmented and Virtual Reality in Construction: Drivers and Limitations for Industry Adoption," *Journal of Construction Engineering and Management*, vol. 146, no. 7, Jul. 2020, Art. no. 04020079, https://doi.org/10.1061/(ASCE)CO.1943-7862.0001844.

[5] A. Atwal, A. Money, and M. Harvey, "Occupational Therapists' Views on Using a Virtual Reality Interior Design Application Within the Pre-Discharge Home Visit Process," *Journal of Medical Internet Research*, vol. 16, no. 12, Dec. 2014, Art. no. e283, https://doi.org/10.2196/jmir.3723.

[6] S. Choi, K. Jung, and S. D. Noh, "Virtual reality applications in manufacturing industries: Past research, present findings, and future directions," *Concurrent Engineering*, vol. 23, no. 1, pp. 40–63, Mar. 2015, https://doi.org/10.1177/1063293X14568814.

[7] P. Wang, P. Wu, J. Wang, H.-L. Chi, and X. Wang, "A Critical Review of the Use of Virtual Reality in Construction Engineering Education and Training," *International Journal of Environmental Research and Public Health*, vol. 15, no. 6, Jun. 2018, Art. no. 1204, https://doi.org/10.3390/ijerph15061204.

[8] S. Ahmed, "A Review on Using Opportunities of Augmented Reality and Virtual Reality in Construction Project Management," *Organization, Technology and Management in Construction: an International Journal*, vol. 11, no. 1, pp. 1839–1852, Feb. 2019, https://doi.org/10.2478/otmcj-2018-0012.

[9] J. Davidson *et al.*, "Integration of VR with BIM to facilitate real-time creation of bill of quantities during the design phase: a proof of concept study," *Frontiers of Engineering Management*, vol. 7, no. 3, pp. 396–403, Sep. 2020, https://doi.org/10.1007/s42524-019-0039-y.

[10] I. Mutis and A. Ambekar, "Challenges and enablers of augmented reality technology for in situ walkthrough applications," *Journal of Information Technology in Construction*, vol. 25, pp. 55–71, Jan. 2020, https://doi.org/10.36680/j.itcon.2020.003.

[11] P. Bhawar, N. Ayer, and S. Sahasrabudhe, "Methodology to Create Optimized 3D Models Using Blender for Android Devices," in *2013 IEEE Fifth International Conference on Technology for Education (t4e 2013)*, Kharagpur, India, Dec. 2013, pp. 139–142, https://doi.org/10.1109/T4E.2013.41.

[12] "The History Of CAD/CAM In Foam Manufacturing," *Technical Foam Services*, May 05, 2020. https://technicalfoamservices.co.uk/blog/blog-history-of-cad-cam/.

[13] F. Moreu, C. Lippitt, D. Maharjan, M. Aguero, and X. Yuan, "Augmented Reality Enhancing the Inspections of Transportation Infrastructure: Research, Education, and Industry Implementation," *Publications*, Aug. 2019, [Online]. Available: https://repository.lsu.edu/transet_pubs/55.

[14] "Bridge Design Specifications," AASHTO, 1998..

[15] "ANSI/AISC 360." American Institute of Steel Construction, [Online]. Available: https://www.aisc.org/publications/steel-standards/aisc-360/.

[16] "Eurocode 8: Design of structures for earthquake resistance | Eurocodes: Building the future." [Online]. Available: https://eurocodes.jrc.ec.europa.eu/EN-Eurocodes/eurocode-8-design-structures-earthquake-resistance.

[17] A. Sadhu, J. E. Peplinski, A. Mohammadkhorasani, and F. Moreu, "A Review of Data Management and Visualization Techniques for Structural Health Monitoring Using BIM and Virtual or Augmented Reality," *Journal of Structural Engineering*, vol. 149, no. 1, Jan. 2023, Art. no. 03122006, https://doi.org/10.1061/(ASCE)ST.1943-541X.0003498.

[18] B. Schiavi, V. Havard, K. Beddiar, and D. Baudry, "BIM data flow architecture with AR/VR technologies: Use cases in architecture, engineering and construction," *Automation in Construction*, vol. 134, Feb. 2022, Art. no. 104054, https://doi.org/10.1016/j.autcon.2021.104054.

[19] S. Meža, Ž. Turk, and M. Dolenc, "Component based engineering of a mobile BIM-based augmented reality system," *Automation in Construction*, vol. 42, pp. 1–12, Jun. 2014, https://doi.org/10.1016/j.autcon.2014.02.011.

[20] S. Safikhani, S. Keller, G. Schweiger, and J. Pirker, "Immersive virtual reality for extending the potential of building information modeling in architecture, engineering, and construction sector: systematic review," *International Journal of Digital Earth*, vol. 15, no. 1, pp. 503–526, Dec. 2022, https://doi.org/10.1080/17538947.2022.2038291.

[21] I. A. Bhatti, A. H. Abdullah, S. Nagapan, N. B. Bhatti, S. Sohu, and A. A. Jhatial, "Implementation of Building Information Modeling (BIM) in Pakistan Construction Industry," *Engineering, Technology & Applied Science Research*, vol. 8, no. 4, pp. 3199–3202, Aug. 2018, https://doi.org/10.48084/etasr.2145.

[22] X. Zhao *et al.*, "Extended Reality for Safe and Effective Construction Management: State-of-the-Art, Challenges, and Future Directions," *Buildings*, vol. 13, no. 1, Jan. 2023, Art. no. 155, https://doi.org/10.3390/buildings13010155.

[23] A. Z. Sampaio and O. P. Martins, "The application of virtual reality technology in the construction of bridge: The cantilever and incremental launching methods," *Automation in Construction*, vol. 37, pp. 58–67, Jan. 2014, https://doi.org/10.1016/j.autcon.2013.10.015.

[24] A. Sadhu, J. E. Peplinski, A. Mohammadkhorasani, and F. Moreu, "A Review of Data Management and Visualization Techniques for Structural Health Monitoring Using BIM and Virtual or Augmented Reality," *Journal of Structural Engineering*, vol. 149, no. 1, Jan. 2023, Art. no. 03122006, https://doi.org/10.1061/(ASCE)ST.1943-541X.0003498.

[25] M. Kurien, M.-K. Kim, M. Kopsida, and I. Brilakis, "Real-time simulation of construction workers using combined human body and hand tracking for robotic construction worker system," *Automation in Construction*, vol. 86, pp. 125–137, Feb. 2018, https://doi.org/10.1016/j.autcon.2017.11.005.

[26] Z. Zhang, F. Wen, Z. Sun, X. Guo, T. He, and C. Lee, "Artificial Intelligence-Enabled Sensing Technologies in the 5G/Internet of Things Era: From Virtual Reality/Augmented Reality to the Digital Twin," *Advanced Intelligent Systems*, vol. 4, no. 7, Jul. 2022, Art. no. 2100228, https://doi.org/10.1002/aisy.202100228.