Applications of VR and AR in Construction Engineering Informatization: Postprint

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Abstract

Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) represent emerging multi-dimensional visualization and communication technologies that have garnered widespread applications across diverse fields. The integrated application of these technologies with Building Information Modeling (BIM) in the architectural engineering domain can harness the strengths of both, thereby achieving mutual complementarity and reinforcement. Throughout the entire building lifecycle, these technologies possess substantial value potential awaiting exploitation. This paper commences from fundamental theoretical underpinnings and conducts an in-depth investigation into the application requirements, practical implementation paradigms, current application status, as well as future development trajectories and potential of this innovative BIMVR/AR fusion technology across the complete lifecycle, encompassing the architectural planning and design phase, engineering construction phase, project marketing phase, and operation and maintenance management phase. Finally, this paper analyzes the obstacles confronting further technological advancement and identifies potential breakthrough avenues.

Full Text

Preamble

Application of VR and AR in the Field of Construction Informatization

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Abstract: Virtual reality (VR), augmented reality (AR), and mixed reality (MR) represent emerging multi-dimensional visual communication technologies with broad applications across various fields. When combined with Building Information Modeling (BIM) in the construction sector, these technologies can

leverage their respective strengths to create synergistic effects. Throughout the entire building lifecycle, there exists substantial untapped value. Beginning with fundamental theory, this paper thoroughly examines the application requirements, implementation models, current status, and future development directions and potential of this innovative BIMVR/AR integration technology across all lifecycle stages, including architectural planning and design, construction, project marketing, and operations and maintenance management. Finally, the paper analyzes the obstacles and breakthrough points for further technological advancement.

Keywords: BIM; Virtual Reality; Augmented Reality; BIMVR; BIMAR

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1 BIMVR/AR Theoretical Foundation

BIMVR (Building Information Modeling in Virtual Reality) is a technical approach that integrates BIM (Building Information Modeling) with VR (Virtual Reality) [Figure 1: see original paper]. While BIM engineers can now create highly realistic BIM models before construction begins, these visual three-dimensional models currently suffer from significant limitations. BIM serves as a new information communication carrier in construction engineering management, and numerous tool software and platform applications based on BIM are emerging like bamboo shoots after rain, gradually replacing traditional CAD drawing-based communication methods. VR/AR/MR are fundamentally new communication technologies, with their related hardware and software becoming new communication tools; they represent the next generation of information processing and communication platforms following computers and mobile phones.

The value potential of BIM+VR/AR/MR for the construction industry will not merely constitute an upgrade of information carriers and tools, but will fundamentally transform the entire information communication paradigm as the technology develops deeply. Integrating BIM with VR technology enables users not only to view models but also to immerse themselves within them, experiencing the sensation of being physically present in the model. This provides ample guidance for both designers and constructors, helping to prevent numerous potential accidents and issues, thereby making project implementation more rational. AR and MR offer similar benefits [Figure 2: see original paper]. BIMVR/AR/MR is poised to become a new communication paradigm for the construction engineering industry, forming a new technical category and interdisciplinary field.

The productivity and informatization level of the construction industry have con-

sistently lagged far behind other industries, fundamentally due to its outdated engineering management and communication paradigms. The industry urgently requires newer, more efficient communication paradigms to innovate and even disrupt this massive sector. So what specific applications does BIMVR/AR/MR have throughout the building lifecycle? The following sections provide detailed introductions.

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2 VR/AR Applications in the Building Lifecycle

2.1 Architectural Planning and Design Phase

(1) BIM+VR Applications

The most fundamental application of BIMVR in the architectural planning and design phase is design scheme review. By immersing designers and reviewers in VR scenes, VR' s unique characteristics enable effects unattainable through conventional paper drawings or screen-based BIM models. Particularly for decision-makers and non-design professionals, VR' s immersive nature allows them to participate actively and contribute evaluations.

Users can examine projects comprehensively from multiple perspectives. For instance, through flying tour viewpoints, they can explore rendered 1:1 BIM model scenes in VR, providing a macro-level perception and judgment of future architectural planning schemes for a region. During these immersive walkthroughs, reviewers can also employ rich VR interaction methods to inspect schemes from all angles and make local modifications and adjustments. When multiple architectural planning and design schemes are available for comparison, VR experiences enable intuitive scheme evaluation and selection. Currently, numerous BIMVR software options are available for the architectural planning and design phase, such as IrisVR, Enscape, Mars, TwinMotion, and Lumion.

(2) BIM+AR/MR Applications

Unlike VR, AR/MR experience scenarios are not confined to indoor experience zones but can be deployed anywhere, such as actual project sites. By exporting model data from BIM software, AR handheld devices and MR glasses can load models and drawings 1:1 at the project site. AR/MR experiences with on-site presence offer superior communication effectiveness for scheme discussions.

As shown in [Figure 2: see original paper], scanning a BIM model at a positioning point on the project site allows design and review personnel to conduct AR walkthrough experiences using iPad devices, exploring the future completed state from any location. MR glasses function similarly, though interaction shifts from touchscreens to gesture and voice controls. Given that ARKit and ARCore were released relatively recently and currently available AR and MR headset devices remain limited, few general-purpose BIMAR/MR software solutions exist for the architectural planning and design phase. Trimble' s Sketchup Viewer

for Microsoft HoloLens, which allows browsing and operating Sketchup-created models, serves as one example. However, most BIMAR applications currently offer limited interactive experiences, primarily consisting of custom-developed project demonstration software.

For custom development, currently available development tools and hardware/software platforms are illustrated in [Figure 3: see original paper].

2.2 Engineering Construction Phase

The engineering management process represents the application of management personnel' s experience and expertise. Traditional engineering managers relied on paper drawings as their information medium, but this is gradually shifting toward electronic and three-dimensional model-based approaches, and even further toward VR and AR implementations. Since engineering management fundamentally involves continuous communication among multiple project participants, BIMVR/AR/MR serve as excellent communication tools with substantial application potential. BIMAR/MR is naturally suited for nearly all communication scenarios at construction sites. It is believed that a series of BIM- and AR/MR-based application tools and platform software will soon be developed to cover all aspects of on-site management.

2.2.1 BIM+VR Applications Early VR applications in the engineering field focused on immersive experiences, leveraging VR' s sense of presence and interactivity for engineering education and training value. As training and education have become more widespread, simple VR experiences no longer satisfy engineering demands, prompting the continuous development of more in-depth applications that excavate the value of BIM and VR for deployment at construction sites. A common BIMVR application architecture is shown in [Figure 4: see original paper]. Currently, BIM+VR applications in the engineering construction phase concentrate primarily on safety management, quality control, schedule control, and organizational coordination.

(1) Safety Management Domain

VR safety management and education represent the earliest implemented applications in the construction phase. Compared to traditional safety training, the advantages of VR safety training are self-evident. By placing workers in construction scenarios to experience various safety accidents and emergency response procedures sequentially, accidents involving injuries or fatalities occurring in VR create psychological deterrent effects through visual, auditory, and tactile feedback. The domestic market demand for VR engineering safety education exceeds that of foreign markets, with greater market potential. VR safety training may become standard equipment at construction sites. Some R&D-oriented enterprises have delved deeply into engineering management, moving beyond superficial projects to develop software with substantial practical value for frontline workers. Taking WanJian' s SafetyVR as an example, the experi-

ence process is detailed in [Figure 5: see original paper]. Beyond conventional safety experience items, SafetyVR incorporates several technological innovations to enhance training effectiveness visibility: a real-name management system using ID card scanning, eye-tracking technology for precise score recording, score management and export for filing purposes ([Figure 6: see original paper]), and comprehensive coverage of multiple project scenarios and accident emergency categories.

Further implementation of BIMVR safety management will feature real-time BIM data import into VR scenes, automatic safety planning and layout, and safety calculation functions, making VR accident experiences optional rather than mandatory. The data value of BIM will be further excavated and highlighted as VR scenes become BIM-data-enabled and BIM scenes become VR-enabled.

(2) Quality Control Domain

VR applications in quality control are primarily used for technical disclosure and training assessment, particularly for complex construction parts of large-scale projects where real-scenario training is difficult. By using BIM models to build VR scenes, setting up interaction processes and assessment standards, training can be conducted effectively. Taking WanJian' s SimVR Fab as an example, the general development process is illustrated in [Figure 7: see original paper]. The depth of VR training disclosure depends on the level of detail in the BIM model, enabling the creation of highly realistic operation processes that can even replicate real scenarios. Two general configuration modes are typically provided: teaching mode and assessment mode.

Engineering quality disclosure and training represent a high-frequency requirement. Engineers and workers need such training daily, suggesting that numerous BIMVR quality disclosure software solutions with simpler information interaction processes will emerge for use by frontline BIM engineering managers. Beyond outputting VR experience results, these systems can directly export high-definition process animation videos and images ([Figure 8: see original paper]) for scheme archiving and other communication scenarios.

(3) Schedule Control Domain

Engineering schedule control emphasizes pre-control. Virtual Design and Construction (VDC) has already become a major academic discipline abroad and a composite professional position within enterprises. VDC engineers utilize BIM models and drawings to conduct virtual simulation and pre-control of construction schedules, identifying and eliminating all detectable unreasonable items and problem points before guiding actual on-site construction, thereby reducing construction uncertainty and the labor, financial, and time costs of rework.

For BIM engineers, simply importing their BIM models into VR scenes, arranging construction schedule sequences, and establishing precise linkages with virtual construction timelines enables complete reproduction of future construc-

tion scenarios in a virtual environment. Managers can rely not only on their construction experience but also on precise data regarding materials, costs, and personnel attached to BIM models to identify optimal construction schedule routes through linear programming methods by adjusting various resource curves, achieving the goal of optimizing construction schemes and reducing construction uncertainty.

The operation process for VR schedule simulation is detailed in [Figure 9: see original paper]. The precision of schedule process simulation correlates with the level of detail in BIM models. As more information resources are linked, more precise data-driven schedule processes can be achieved. After establishing the schedule simulation process, engineers can wear headsets to enter VR scenes and review process details to assess the implementability of virtual construction schemes, preventing local process conflicts. With further integration of BIM and VR, generalized BIMVR software will become production tools for site foremen, material officers, and other management positions closely related to schedules. Additionally, remote multi-user simultaneous online VR experiences will become more common and practical, enabling remote multi-party collaborative communication among construction units, contractors, design units, and supervision units within VR scenes, significantly improving work efficiency and saving communication costs without requiring physical presence.

2.2.2 BIM+AR Applications Although currently not widespread in the construction management phase, BIMAR/MR applications possess scenario advantages that may surpass those of VR. The communication object in BIMAR/MR is no longer purely virtual BIM models but rather the interaction between BIM models and the on-site environment. Moreover, the communication participants are no longer limited to construction managers or workers interacting with models but involve multi-party coordinated communication.

The development roadmap for BIMAR/MR platform software is illustrated in [Figure 10: see original paper]. Current BIMAR applications are primarily developed based on Apple' s ARKit interface for iOS systems, compatible with the latest iPhone and iPad series devices. Applications based on Android' s ARCore remain rare due to limited compatible models, though this is expected to change soon as numerous mobile phones and tablets will support smooth AR functionality, substantially reducing AR experience costs. Current BIMMR applications mainly target Microsoft HoloLens glasses, with the recently released Magic Leap One offering improved performance and experience over HoloLens, suggesting potential applications in construction engineering.

Taking WanJian's Mr.BIM as an example, BIMAR/MR application points in the construction engineering management phase primarily include: (1) Positioned tour: BIM model QR code initial positioning setup ([Figure 11: see original paper]), AR scene roaming, and information viewing; (2) Virtual measurement and layout: layered display of construction drawings and models, virtual layout positioning, and accurate AR measurement ([Figure 12: see original paper]); (3)

On-site construction guidance: installation process guidance and synchronous technical disclosure; (4) Quality acceptance: verification of drawings and models against actual structural positions, identifying and recording quality deviations.

2.3 Project Marketing Phase

VR/AR' s earliest applications in the construction industry were in project marketing and promotion, particularly for real estate projects where VR showrooms have become standard equipment in many project marketing centers. Numerous startup enterprises both domestically and internationally engage in customized VR content development services for real estate marketing. VR/AR' s intuitive communication and expression capabilities can clearly convey project characteristics and advantages to non-professional client groups in refreshing ways. For projects that have begun sales during early construction phases, importing BIM models into VR/AR engines, performing detailed rendering adjustments, and supplementing them with interactive programs can fully reproduce the operational state of completed construction projects, accurately communicating with potential customers, owners, and the general public.

2.3.1 BIM+VR Applications VR applications primarily consist of VR showrooms, VR property displays, and VR exhibitions, presenting completed project scenes through VR environments to potential customers or the public. The general workflow is illustrated in [Figure 13: see original paper]. A typical VR showroom project marketing display system includes VR display modules for area planning, property display, unit VR interaction, design concepts, decoration scenarios, and home design experiences, integrated with conventional marketing content such as enterprise display, platform overview, decoration lists, main material introductions, delivery standards, and service systems. For instance, by reproducing future living scenarios within buildings in VR scenes ([Figure 14: see original paper], a VR marketing case demonstrating the intelligent grocery shopping function of a smart refrigerator), accurate marketing objectives can be achieved.

2.3.2 BIM+AR Applications AR/MR applications in project marketing are similar to VR. AR experiences are generally integrated into mobile applications as AR model display functions, activated through QR code scanning to load models and information. Image recognition-based AR experiences currently support nearly all Android and iOS mobile devices. AR experiences relying on SLAM real-time positioning remain limited in options and require high hardware performance. Consequently, current mainstream and simple AR applications predominantly adopt image recognition modes, such as card recognition-based AR model display experiences developed using the Vuforia SDK.

Mobile AR application solutions based on Apple' s ARKit and Google' s ARCore represent a mainstream direction with potential for developing generalized AR applications. Several enterprises are already exploring this area, with IKEA' s

AR application IKEA Place serving as a typical example. IKEA Place includes over 2,000 furniture BIM models ([Figure 15: see original paper]), allowing users to fully exercise their imagination in designing their spaces within AR.

2.4 Operations and Maintenance Management Phase

Building operations and maintenance (O&M) management refers to the comprehensive management conducted after building completion and commissioning, integrating key resources such as personnel, facilities, and technology within the building to maximize utilization rates, reduce operating costs, increase investment returns, and extend building lifecycles through maintenance. Completed buildings or structures enter usage periods lasting decades or even centuries, all involving operation, maintenance, warranty, and renewal. Particularly for equipment-intensive buildings such as machine rooms and factories, facility failures require immediate maintenance. However, numerous hidden engineering works exist, and historical drawing archives are difficult to locate, making the value of BIM data-based VR/AR/MR applications in construction engineering prominently evident.

2.4.1 BIM+VR Applications (1) Commissioning Simulation Training

During the trial operation phase after project completion, BIMVR scenes can simulate operational scenarios, known as VR Commissioning. For a production factory, VR can precisely simulate operating conditions of various equipment. Commissioning simulation content includes equipment operation condition simulation, fire emergency drill simulation, and typical equipment failure emergency drill simulation.

(2) VR+IoT Remote Operation

VR technology combined with IoT hardware for construction engineering facilities can visualize equipment operation data in real-time within VR scenes. Furthermore, by operating virtual hardware facilities within VR scenes, instructions can be transmitted to actual building hardware controllers to achieve remote control, as illustrated in [Figure 16: see original paper]. For equipment areas with high operational risks, remote operation in VR scenes enhances safety while remaining simple, intuitive, and convenient. Real-time operational data of facilities and equipment can also be viewed within VR scenes, allowing operators to manage all connected equipment throughout the building from the control room experience zone. [Figure 17: see original paper] presents a case of VR remote operation of machine tools in a steel factory, where operators holding controllers manipulate virtual equipment in VR scenes while controlling physical building equipment identical to the virtual devices.

2.4.2 BIM+AR Applications A typical case illustrates AR/MR applications: the globally renowned elevator manufacturer ThyssenKrupp developed

a dedicated BIM+MR O&M and inspection management system based on Microsoft HoloLens, networking elevator equipment operation data and displaying it through MR glasses to guide on-site maintenance personnel and improve work efficiency, as shown in [Figure 18: see original paper].

Upon receiving maintenance notifications, maintenance personnel open MR devices to view equipment information and fault status of elevators awaiting repair. All model and document data information is then displayed in space through MR glasses, with all hidden engineering information also shown. When encountering issues that cannot be diagnosed, remote assistance can be sought by synchronizing headset camera footage with other personnel. After maintenance completion, real-time equipment operation information and work order details can be viewed in real-time through MR glasses and synchronized to the server. Throughout this process, MR information augmentation assistance significantly shortens traditional inspection processes based on drawings, detection equipment, and experience, substantially improving work efficiency.

Innovative applications similar to ThyssenKrupp' s BIMMR system can be extended to all aspects of construction engineering O&M management, enabling AR/MR technology to assist O&M personnel in working efficiently. BIM data for buildings in the O&M phase is updated in real-time, constituting a set of digital virtual assets. VR/AR/MR provides management personnel and owners with a medium for communicating and interacting with these data assets, allowing the assets to deliver value throughout the O&M lifecycle.

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3 Development Trends and Obstacles

3.1 Development Trends

BIMVR/AR/MR holds crucial applications throughout the building lifecycle and has the potential to become a disruptive communication management technology in communication-intensive domains. However, the technology remains immature, and its further implementation requires extensive innovative R&D and exploration. The formation of new management communication paradigms in the construction industry will not occur overnight. The BIMVR/AR/MR development roadmap is illustrated in [Figure 19: see original paper]. For the construction industry, particularly during the engineering construction phase, AR/MR application scenarios far exceed VR scenarios. Virtually anywhere communication is required, AR/MR can replace traditional inefficient communication methods.

Currently, BIMVR development has achieved certain maturity, BIMAR applications are on the rise, and BIMMR applications remain limited to pilot projects. BIMMR represents the most convenient application method. As software development costs decrease and MR hardware gradually matures and becomes popularized, BIMMR applications may dominate construction sites, with MR

wearable equipment potentially becoming as standard as safety helmets for construction industry engineering personnel.

After AR/MR hardware costs decrease and performance improves, application distribution will also simplify. With the popularization of 5G communication technology, real-time transmission of BIM model data will no longer pose challenges, enabling BIMAR/MR to evolve from early standalone software applications toward continuous cloudification. Users will be able to complete on-site communication experience processes through pure Web applications, forming a small front-end (AR/MR device side) and large back-end (cloud) application model. An increasing number of tool-level BIMVR/AR/MR software and platforms will emerge, covering various engineering sub-domains, particularly those closely related to BIM model-based communication.

3.2 Obstacles and Breakthroughs

Obstacles to VR/AR/MR development in the construction industry are multifaceted, primarily including: (1) relatively low industry practitioner quality and slow adoption of new technologies; (2) slow BIM technology development, which affects the 普及 application of BIMVR/AR/MR to varying degrees; and (3) VR/AR/MR hardware technology and costs still having significant gaps from 普及 application.

The construction industry' s profit margins are generally very low. If new technology introduction can deliver value through project management cost reduction, quality improvement, and efficiency enhancement, the entire industry will readily embrace new technologies. Breakthrough points for the 普及 application of BIMVR/AR/MR include: (1) reduction in VR/AR/MR hardware costs and performance improvements; and (2) emergence of rigid-demand, easy-to-use BIMVR/AR/MR application software.

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Note: Figure translations are in progress. See original paper for figures.