IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received 14 April 2025, accepted 10 May 2025, date of publication 14 May 2025, date of current version 21 May 2025.

Digital Object Identifier 10.1109/ACCESS.2025.3570166

SURVEY

Immersive Multiplayer VR: Unreal Engine's Strengths, Limitations, and Future Prospects

SANTIAGO BERREZUETA-GUZMAN, AND STEFAN WAGNER, (Senior Member, IEEE)
Chair of Software Engineering, Technical University of Munich, 74076 Heilbronn, Germany

Corresponding author: Santiago Berrezueta (s.berrezueta@tum.de)

This research was financially supported by the TUM Campus Heilbronn Incentive Fund 2024 of the Technical University of Munich, TUM Campus Heilbronn. We gratefully acknowledge their support, which provided the essential resources and opportunities to conduct this study.

ABSTRACT Virtual Reality (VR) has revolutionized digital interactions, particularly in multiplayer games, where players engage in immersive experiences that foster social connectivity and collaboration. Unreal Engine is at the core of this evolution, a powerful development platform known for its advanced networking tools, VR-specific capabilities, and seamless cross-platform support. Unreal Engine's cross-platform support also ensures accessibility and scalability across diverse devices. This paper analyzes Unreal Engine's role in advancing multiplayer VR development, focusing on its ability to create immersive environments that enhance user engagement and social interaction. We examined key features such as real-time networking for seamless communication, detailed avatar customization, and realistic environmental rendering, all contributing to an enhanced sense of presence. Beyond its technical features, this research identifies key challenges in multiplayer VR gaming, including latency, scalability, and ethical concerns related to inclusivity and user privacy. We propose future directions to address these issues, such as integrating artificial intelligence (AI), enhancing haptic feedback, and optimizing large-scale VR projects. By bridging these gaps, Unreal Engine can strengthen its role as a pioneering platform for social interaction, education, and collaboration in virtual spaces. This study also evaluates Unreal Engine's effectiveness in facilitating social interaction and compares its capabilities with alternative platforms. The findings highlight best practices for VR game developers and provide recommendations to enhance user engagement and accessibility, ensuring that multiplayer VR continues to evolve as a transformative medium.

INDEX TERMS
AI-driven VR interactions, avatar customization, cross-platform VR development, haptic feedback in VR, immersive environments, literature review, multiplayer virtual reality (VR), real-time VR communication, scalability in multiplayer VR, social interaction in VR, unreal engine.

I. INTRODUCTION

Virtual Reality (VR) fosters innovation in digital interaction, creating immersive experiences using recent technological advances, such as full-body motion tracking, real-time physics-based interactions, and haptic feedback systems, which have transformed how users engage with virtual environments. These breakthroughs enabled realistic simulations and tactile experiences that mirror real-world dynamics, fundamentally shifting the landscape of digital interaction [1]. Early VR applications focused on sensory immersion, using visual and auditory stimuli to replicate real-world scenarios. Today, the focus has shifted toward interactive and networked environments, where players engage in real-time collaboration, learning, and entertainment [2].

The evolution of VR technology has progressed from single-user experiences to complex multiplayer platforms that allow dynamic and immersive social interactions. These environments bridge physical distances, allowing users to communicate, collaborate, and interact in shared virtual spaces [1]. Multiplayer VR games provide realistic social

The associate editor coordinating the review of this manuscript and approving it for publication was Tai-Hoon Kim.

experiences, making them an ideal environment to analyze human behavior in digital interactions [3].

The intersection of VR gaming and social interaction refers to how multiplayer VR environments facilitate meaningful user engagement, communication, and collaboration. Unlike traditional video games, where players engage in predefined interactions, multiplayer VR offers a realistic sense of presence, enabling non-verbal communication, shared experiences, and cooperative gameplay in a way that closely mimics real-world social dynamics [2]. This unique capability positions multiplayer VR as an ideal platform for studying and enhancing digital socialization.

Numerous engines support the development of multiplayer VR applications. *Unity* is widely used due to its large developer community and cross-platform capabilities. *Godot* has recently gained attention for its open-source flexibility and lightweight architecture. Proprietary platforms like *Meta's Presence Platform* offer hardware-integrated solutions optimized for social presence and hand tracking. While this study focuses on Unreal Engine, it does so not to assert its superiority but to analyze its distinctive features and growing relevance in this domain.

Unreal Engine is a cutting-edge game development platform recognized for its robust networking capabilities, VR-specific tools, and cross-platform functionality. It enables developers to create multiplayer VR experiences that enhance digital interaction and user engagement [4].

However, its role in shaping multiplayer VR's social dynamics remains underexplored. While research has analyzed VR social behavior and networking technologies separately [5], a comprehensive study of Unreal Engine's impact on multiplayer VR socialization is still lacking. Given its growing influence in virtual collaboration and entertainment, a structured analysis of its contributions is essential [6].

To bridge this gap, this study seeks to explore the following key research questions (RQ):

- **RQ1.** How can Unreal Engine enhance social interaction in multiplayer VR environments?

- **RQ2.** What are the strengths and limitations of Unreal Engine for fostering multiplayer VR experiences?

- **RQ3.** What are the technical and ethical challenges of developing multiplayer VR applications with Unreal Engine?

- **RQ4.** What are the research directions and best practices for optimizing Unreal Engine's capabilities in multiplayer VR development?

Understanding how Unreal Engine facilitates user-to-user interaction in virtual spaces is critical as VR adoption grows.

To answer the *RQs*, this paper analyzes trends and challenges in multiplayer VR applications, focusing on Unreal Engine's role. By examining advanced networking tools, avatar customization, VR-specific functionalities, and cross-platform support, we evaluate the current state of multiplayer VR development, identify its limitations, and explore future directions. Additionally, we highlight best practices for enhancing user engagement, accessibility, and scalability across key domains such as entertainment, education, and virtual collaboration.

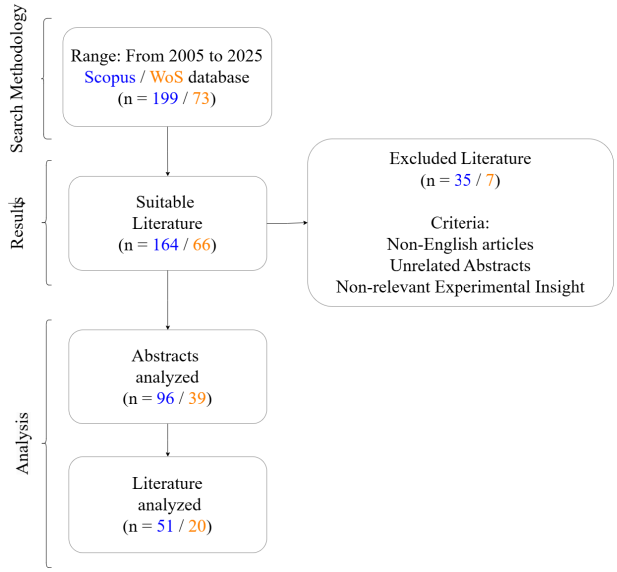

FIGURE 1. Flowchart of the literature selection and analysis process applied in this SLR.

This paper is structured as follows: Section II outlines the methodology, detailing the systematic review process and selection criteria. Section III explores techniques for fostering social interaction in multiplayer VR, including avatar customization and immersive design. Section IV examines Unreal Engine's key features, such as networking tools, VR-specific functionalities, and cross-platform support. Section V discusses applications in entertainment, education, and virtual conferencing. Section VI addresses key challenges and ethical considerations, including scalability and inclusivity. Section VII presents future research directions, while Section VIII provides guidelines for developers. Finally, Section IX concludes by highlighting Unreal Engine's transformative role in advancing multiplayer VR experiences.

II. METHODOLOGY

This study employs a systematic literature review (SLR) combined with a qualitative thematic analysis to explore the intersection of multiplayer VR gaming, social interactions, and Unreal Engine's role.

A. DATA COLLECTION AND SELECTION CRITERIA

Relevant literature was collected from top academic databases, as shown in Figure 1. This review includes sources from Scopus and Web of Science (WoS), which index peer-reviewed articles from IEEE Xplore, ACM Digital Library, SpringerLink, and other reputable platforms. The search strategy focused on key terms such as "Unreal Engine," "multiplayer VR," "social interaction in VR," and "cross-platform VR gaming" to ensure a comprehensive selection of relevant studies.

Inclusion Criteria: Peer-reviewed articles, technical reports, and case studies published from 2005 to 2025, focusing on Unreal Engine's networking, VR-specific functionalities, and applications in multiplayer VR environments.

Exclusion Criteria: Non-peer-reviewed sources, commercial white papers, studies lacking technical depth, and research unrelated to VR multiplayer experiences.

Although Unreal Engine's VR capabilities emerged around 2014 with Unreal Engine 4, we selected 2005 as the starting point to capture the early academic discussions on multiplayer VR technologies, immersive environments, and foundational networking frameworks. This broader historical context helps identify how technical demands and design principles evolved before modern engine support became widespread.

B. ANALYSIS APPROACH

The collected studies were examined through qualitative thematic analysis, identifying key themes such as networking challenges, social interaction dynamics, AI-driven enhancements, and ethical considerations in multiplayer. Studies were categorized using thematic coding into avatar customization, haptic feedback, cross-platform scalability, and AI in VR. A limited quantitative analysis was also conducted to track publication trends and research focus.

Specifically, we extracted bibliometric metadata (e.g., publication year, keywords) from Scopus and Web of Science for all included studies and used descriptive statistics to visualize the annual growth in the relevant literature. This analysis helped us identify key periods of increased academic attention to multiplayer VR development and Unreal Engine adoption. Figure 2 visualizes this data, focusing on the period from 2005 to 2025, with greater granularity for 2015 to 2025, when Unreal Engine's VR capabilities became more prominent.

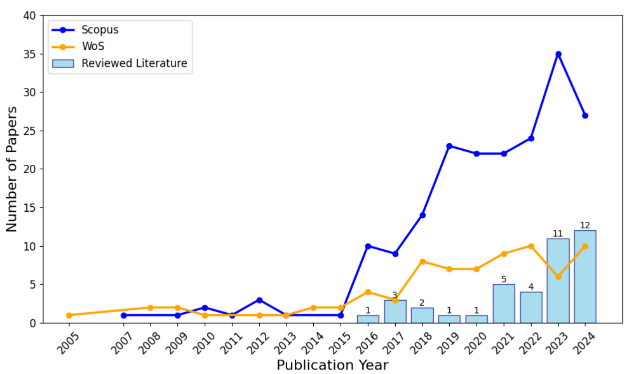

FIGURE 2. Number of publications analyzed in Scopus and Web of Science (WoS) per year from 2005 to 2025, along with the subset of this review from 2015 to 2025.

III. TECHNIQUES FOR FOSTERING SOCIAL INTERACTION IN MULTIPLAYER VIRTUAL REALITY ENVIRONMENTS

Fostering social interaction in multiplayer Virtual Reality (VR) involves leveraging techniques such as avatar customization, immersive environmental design, and robust communication systems. Together, these techniques strengthen social bonds and collaboration in multiplayer VR settings.

A. AVATAR DESIGN AND CUSTOMIZATION

Design and personalization of avatars play a pivotal role in fostering social interaction within multiplayer VR environments, as these visual and behavioral representations enable users to communicate and collaborate effectively in virtual spaces. By customization, avatars enhance user engagement by fostering a sense of ownership, individuality, and social identity—key elements that underpin meaningful interactions and connections in immersive virtual worlds [7], [8].

Recent research highlights the significant impact of avatar representation on social connectedness and self-esteem, showing that enabling users to self-represent through avatars reinforces their sense of identity and fosters a feeling of belonging and acceptance [9].

Among the advancements enhancing social dynamics in VR is the development of realistic motion avatars, replicating human movement and facial expressions to make virtual interactions more lifelike [10]. Powered by motion capture technology and AI-driven algorithms, these innovations enable immersive experiences and strengthen identity perception through features like full-body tracking and realistic gestures [11].

The psychological impact of avatar personalization extends beyond identity representation. Freeman et al. [8] demonstrated that highly customizable avatars enhance social presence and user involvement in virtual communities. This personalization allows users to express their identity, preferences, and roles while fostering trust, empathy, and communication by balancing self-expression with adherence to social norms in virtual worlds.

The design and personalization of avatars significantly influence pro-social behavior in multiplayer VR environments. Design decisions regarding appearance and interaction features play a pivotal role in shaping positive social dynamics, with realistic avatars enhancing trust and empathy, encouraging creativity and exploration of alternative identities [12].

On the same line, Manninen et al. [13] emphasized the crucial role of avatars in shaping social interactions within VR. Their study highlights how avatars create dynamic communication spaces by enabling rich non-verbal cues, fostering authenticity, and promoting pro-social behaviors.

B. ENVIRONMENTAL DESIGN FOR ENGAGEMENT

Well-designed virtual environments elicit an increased engagement of users in collaborative activities, enhancing their sense of presence and allowing them to interact intuitively with each other, especially in the scope of a walkthrough [14].

The study by Du et al. [15] underscored the advantages of designing shared virtual spaces that facilitate interaction between VR and non-VR players. This inclusive approach fosters active participation and enhances engagement by creating experiences tailored to diverse user platforms. Crucial elements, such as visually rich environments and spatial audio, play a key role in immersing users and maintaining their involvement. Additionally, the study highlights the significance of user-friendly interaction designs and compatibility between VR and non-VR systems, addressing potential challenges and enabling seamless collaboration.

Liszio et al. [16] examined how virtual spaces can simulate the sensation of physical presence with others, emphasizing the importance of features like spatial audio, realistic avatar movements, and interactive objects in maintaining user engagement. However, they also highlighted challenges in designing these features, such as disruptions to communication and interaction. To address these issues, the researchers proposed solutions, including optimizing the layout of virtual spaces and enhancing the responsiveness of virtual elements, ultimately aiming to improve the overall user experience.

Sykownik et al. [17] examined how environmental design influences social presence, a key factor in multiplayer VR engagement. Their study highlighted how simulating co-located experiences enhances social presence and meaningful interaction. By focusing on innovative methods for co-location, they provided valuable insights for designing VR environments that foster social and collaborative engagement.

C. COMMUNICATION SYSTEMS

Effective communication systems form the backbone of any multiplayer VR environment, enabling meaningful social interactions that help to reduce feelings of isolation and improve the overall user experience. Research highlights the critical role of communication systems in fostering social connectedness and alleviating feelings of isolation. Lee et al. [9] demonstrated that well-designed tools, including voice chat, gestures, and shared virtual spaces, can significantly enhance users' social experiences. Such features facilitate collaboration and minimize misunderstandings, strengthening community-building efforts within virtual environments [18].

Also, avatar personalization is crucial in enhancing communication within VR environments. As highlighted by Radiah et al. [7] personalized avatars enable users to express emotions and intentions naturally and effectively, with non-verbal cues like facial expressions and gestures. These features enhance communication clarity, foster empathy, and promote cooperation, ultimately reducing misunderstandings and encouraging positive social exchanges.

Moreover, incorporating voice modulation, detailed facial expressions, and gesture-based interactions further enriches communication. Freeman et al. [8] emphasize that greater identification with avatars enhances verbal and non-verbal interactions, facilitating more collaborative and socially engaging VR experiences.

D. LIMITATIONS AND CHALLENGES IN FOSTERING SOCIAL INTERACTION

Despite significant advances, several challenges persist in enabling seamless social interaction in multiplayer VR environments.

First, the computational overhead required for realistic motion capture—including full-body tracking, facial expression rendering, and inverse kinematics—can place high demands on client and server hardware. This can limit accessibility for users with lower-end systems or standalone VR headsets.

Second, real-time interaction is sensitive to network latency and bandwidth constraints. Even minor synchronization issues can break the illusion of presence and lead to fragmented communication, especially in geographically distributed multiplayer settings [15].

Third, ensuring accessibility remains a critical challenge. Many systems rely on gesture-based or voice inputs, which may exclude users with motor, auditory, or cognitive impairments. Universal design strategies and inclusive development practices are necessary to make social VR experiences equitable for all [9].

IV. UNREAL ENGINE'S MULTIPLAYER AND VIRTUAL REALITY CAPABILITIES

Unreal Engine provides a comprehensive suite of tools and features, making it a leading platform for developing multiplayer Virtual Reality (VR) experiences.

A. NETWORKING TOOLS FOR REAL-TIME INTERACTION

Unreal Engine is a powerful platform for creating multiplayer VR applications due to its advanced networking tools for real-time interaction. A software template for multi-user VR environments provides essential insights into architectural considerations and implementation strategies for networking in multiplayer settings, showcasing foundational frameworks for seamless collaboration [19].

Unreal Engine version 5 further simplifies the addition of multiplayer functionalities explicitly tailored for VR, as detailed in practical guides and development resources [20]. Similarly, using *C++* in VR multiplayer creation highlights the engine's ability to handle complex networking requirements, optimizing real-time user experiences [21].

Performance evaluations comparing different networking frameworks highlight Unreal Engine's efficiency in VR applications, demonstrating its ability to handle complex interactive environments [22]. Its comprehensive documentation covers key topics such as replication systems, network optimization, and multiplayer architecture, equipping developers with the tools to enhance networking performance [6]. Additionally, specialized tools like the *VR Expansion Plugin* help overcome challenges in multiplayer VR, providing advanced solutions for locomotion and object interaction, essential for creating immersive experiences [23].

Community discussions on platforms like Reddit[1] provide practical solutions to common issues in multiplayer VR development [6]. Similarly, the *Meta*[2] eXtended Reality (XR) Interaction Software Development Kit (SDK) enhances social presence through intuitive interactions, enriching the multiplayer experience [26].

Unreal Engine's networking framework analyses emphasize its scalability, real-time replication, and server capabilities, reinforcing its role in creating dynamic and socially immersive VR environments. Combined with its extensive toolkit, strong community support, and technical flexibility, Unreal Engine remains a top choice for developing advanced multiplayer VR applications [23].

B. SPECIFIC FEATURES FOR VIRTUAL REALITY

Unreal Engine offers a comprehensive set of VR-specific features, making it a powerful tool for developing immersive and socially engaging multiplayer experiences. It also supports XR, seamlessly integrating Virtual, Mixed, and Augmented Reality (AR) applications [27].

Its flexibility allows developers to build tools and frameworks that enhance social interaction in multiplayer environments [28]. For instance, Unreal Engine's ability to render complex data in VR, such as neural network visualizations, showcases how it merges advanced technical processes with engaging user experiences [29].

Avatar functionality is central to VR social platforms, highlighting Unreal Engine's role in enhancing social presence. Its tools enable detailed avatar creation and interaction, essential for fostering realistic and meaningful engagement in virtual environments [28], [30].

Unreal Engine natively supports cross-platform compatibility and advanced rendering features, including *Nanite*. This virtualized geometry system ensures high performance and realistic visual fidelity while maintaining smooth multiplayer interactions [31], [32], [33]. This is crucial for VR environments, where immersive realism is key to user experience. Additionally, the engine is highly extensible, supporting plugins like *UnrealHaptics*, which integrate haptic feedback to enhance realism and user engagement in multiplayer VR games [34], [35].

Unreal Engine provides robust frameworks and best practices that simplify VR application development. The *Gameplay Ability System (GAS)* offers a modular approach for managing complex multiplayer interactions, enabling efficient character ability handling. The *Replication Graph* optimizes network performance by selectively distributing data to relevant players, ensuring seamless synchronization. *Motion Warping* enhances VR locomotion by dynamically adjusting animations for more realistic movement [6].

To maintain high-fidelity graphics across diverse VR hardware, Unreal Engine also integrates *Lumen* global illumination, optimizing real-time rendering without performance loss. Additionally, the *XR Interaction Toolkit* supports hand tracking, gesture recognition, and haptic feedback, making VR interactions more immersive and natural. By leveraging these structured methodologies, developers can enhance user experience, scalability, and engagement in multiplayer VR environments [6].

The practical applications of these capabilities further underscore their impact. For example, educational VR games developed using Unreal Engine often incorporate principles of embodied cognition, enabling deeper engagement and enhanced learning experiences [30]. Similarly, creating virtual assembly applications with it testifies to its efficiency and versatility in various development scenarios [36]. With these attributes, Unreal Engine is very well placed as a leading platform for VR development: it can create immersive, interactive, and socially engaging multi-user experiences.

C. CROSS-PLATFORM SUPPORT

Unreal Engine's robust cross-platform support has proven instrumental in developing multiplayer VR games that operate seamlessly across various devices. The development practices of *STRIDE*, a VR game created by Joy Way, illustrate how Unreal Engine enables effective handling of platform-specific code and integration with custom backend services, ensuring smooth cross-platform multiplayer experiences [37].

However, achieving consistent performance across high-end PCs and standalone headsets (such as Meta Quest or Pico Neo) poses significant challenges. These include discrepancies in processing power, GPU capability, memory limits, and rendering techniques. While desktop VR can support high-polygon models, dynamic lighting, and complex shaders, standalone headsets often require aggressive optimization due to limited computational resources and battery life.

To address these discrepancies, developers must adopt a range of optimization strategies. Common techniques include:

- **Level-of-Detail (LoD) Systems**: Dynamically adjusting model complexity based on distance to reduce rendering overhead.
- **Occlusion Culling**: Preventing the rendering of off-screen or hidden objects to reduce GPU load.
- **Texture Streaming and Compression**: Loading textures on demand with adjustable resolutions.
- **Adaptive Resolution Scaling**: Dynamically lowering resolution in real-time to maintain frame rate targets.
- **Platform-Specific Rendering Paths**: Using conditional rendering or alternate assets optimized for specific hardware.

[1]Reddit is a social media platform where users share insights, discuss challenges, and vote on solutions across various topics [24].

[2]Meta is a technology company specializing in social media, VR, and AI, known for platforms like Facebook and the Meta Quest VR headset [25].

Unreal Engine's modular architecture and support for conditional compilation allow developers to implement these strategies effectively. Furthermore, plugins like Oculus' Mobile SDK for Unreal provide additional support for optimizing standalone VR hardware. By leveraging these approaches, developers can create scalable VR experiences that maintain visual fidelity and interactivity across various devices, enhancing accessibility and broadening user adoption.

Similarly, best practices outlined in academic research emphasize the importance of maintaining a consistent user experience across diverse VR devices, leveraging the engine's tools for optimization and compatibility [38], [39].

Innovative industrial training applications further showcase Unreal Engine's ability to create immersive metaverses, demonstrating consistent performance across devices and highlighting its suitability for cross-platform VR environments [40]. Integration strategies discussed in industry articles reveal how Unreal Engine supports maximum visual realism across platforms, emphasizing flexibility and user experience uniformity in multiplayer VR contexts [41].

By facilitating real-time rendering and multi-platform optimization, Unreal Engine empowers developers to build games for multiple platforms from a single codebase, streamlining the development process [38]. The engine's versatility extends to mobile VR gaming, where its cross-platform capabilities ensure optimized performance and accessibility [38].

Practical applications, such as developing the VR game *MusicMan*, demonstrate Unreal Engine's effectiveness in implementing VR-specific features while ensuring cross-platform compatibility [36]. Additionally, discussions on the engine's advantages and limitations for mobile development provide valuable insights into its role in supporting cross-platform mobile VR [42]. These findings highlight Unreal Engine's critical contribution to enabling high-quality, scalable multiplayer VR experiences across various platforms.

D. LIMITATIONS OF UNREAL ENGINE IN MULTIPLAYER VR DEVELOPMENT

While Unreal Engine provides a powerful toolkit for multiplayer VR, it also presents certain limitations. The platform has high system requirements, especially when leveraging advanced features like Nanite, Lumen, and high-fidelity shaders. These performance demands can limit deployment on lower-end systems and standalone headsets.

Additionally, Unreal Engine is known for its steep learning curve, particularly for developers unfamiliar with *C++* or its proprietary systems like the Gameplay Ability System (GAS). This can increase onboarding time and reduce accessibility for smaller development teams or educational use.

Network scalability presents another challenge. Although Unreal Engine offers tools such as the Replication Graph for optimizing network traffic, deploying large-scale multiplayer VR experiences still requires substantial server infrastructure, careful replication management, and manual performance tuning to avoid bottlenecks and desynchronization [43].

Recognizing and addressing these limitations is essential to unlock Unreal Engine's full potential in scalable and inclusive multiplayer VR development.

V. APPLICATIONS OF MULTIPLAYER VIRTUAL REALITY GAMES BUILT WITH UNREAL ENGINE

Multiplayer Virtual Reality (VR) games developed with Unreal Engine revolutionize how virtual environments are used across domains. By offering immersive, interactive, and socially engaging experiences, these games go beyond entertainment, opening new possibilities in entertainment, education, professional collaboration, and virtual conferencing [44].

Developers often choose Unreal Engine over other platforms, such as Unity or Godot, for multiplayer VR projects due to its superior out-of-the-box networking capabilities, high-fidelity rendering pipeline, and performance optimization tools. While Unity is widely adopted for mobile VR and benefits from a large asset ecosystem, Unreal Engine offers key advantages for complex multiplayer scenarios, including native support for server-authoritative architectures, the Replication Graph system for efficient network scaling, and the powerful Gameplay Ability System (GAS) for modular multiplayer mechanics. Additionally, Unreal Engine's integration with advanced rendering technologies like Nanite and Lumen allows developers to create immersive visuals without sacrificing performance, which is particularly important in high-end VR. These features make Unreal Engine a preferred choice for AAA studios and indie developers aiming to build scalable, visually rich, and socially engaging multiplayer VR experiences.

A. ENTERTAINMENT

Multiplayer VR games developed with Unreal Engine transform the entertainment industry by offering immersive and interactive experiences that redefine digital media consumption. Notable examples include STRIDE (Joy Way), a fast-paced parkour action game, and Rec Room, a social VR platform centered on user-generated content and multiplayer interaction. Both leverage Unreal Engine's advanced physics and networking capabilities to deliver seamless, cross-platform gameplay [45], [46].

Rogers et al. [47] highlighted Unreal Engine's ability to support development across multiple platforms, making it essential for creating engaging experiences in the entertainment industry. Similarly, Sensorium Corporation's social VR platforms for music festivals demonstrate how Unreal Engine facilitates dynamic and immersive multiplayer interactions, showcasing its versatility in delivering captivating virtual entertainment [48].

Research on VR gaming highlights how immersive design enhances user engagement [49]. Jungherr et al. [50] analyzed

VR's impact on the entertainment industry, discussing emerging trends and emphasizing Unreal Engine's key role in these developments. Similarly, Sykownik et al. [17] provided insights into shared experiences among remote players, laying the groundwork for advancements in multiplayer VR, including improved co-presence, realistic interactions, and scalable systems for large-scale environments.

Chan et al. [51] provided practical guidance on how to build compelling multiplayer VR experiences. They cover key strategies like managing server-client systems, reducing latency for smoother interactions, and using player feedback to improve engagement.

Satalin et al. [52] emphasize Unreal Engine's key role in creating robust multiplayer and networking systems, highlighting its flexibility and scalability for developing socially enriching VR applications. Tools like the replication framework and *Blueprint* system simplify development, making it accessible even for developers with limited networking experience.

Finally, Marques et al. [21] provided a comprehensive guide on implementing VR multiplayer environments, solidifying Unreal Engine's importance in developing collaborative and interactive entertainment experiences. This includes detailed strategies for optimizing network performance, managing latency in real-time interactions, and designing intuitive user interfaces that enhance player engagement.

B. EDUCATION

Multiplayer VR games built with Unreal Engine offer immense potential for education, enabling innovative engagement. For example, *VR Sketch* facilitates architectural design in an interactive 3D space, utilizing real-time rendering and AI-driven modules for hands-on learning [53]. Research also highlights Unreal Engine's effectiveness in teaching architectural concepts, reinforcing its value in education [54].

The research conducted by Almeida et al. [40] highlighted the use of Unreal Engine in developing cross-platform VR environments, spanning applications from industrial training to immersive education. Their study emphasizes the platform's ability to provide high-quality graphics, seamless interactions, and consistent performance across various devices.

In a randomized controlled trial, Lowry et al. [55] evaluated the effectiveness of a merged virtual reality (MVR) platform for teaching the Fundamentals of Laparoscopic Surgery skills. The study involved 30 participants in three groups: one received traditional in-person instruction, another received identical training via the MVR platform, and a control group practiced independently without feedback. Results indicated that the MVR-based instruction was non-inferior to conventional in-person training, with both groups showing significant improvements over the control group in tasks such as ligating loop, extracorporeal suturing, and intracorporeal suturing. These findings suggest that MVR platforms can effectively facilitate remote surgical education, offering a viable alternative to traditional methods, especially in limited in-person training.

Furthermore, Fischer et al. [56] supported Unreal Engine's capacity to create collaborative virtual spaces, enhancing interactive learning through immersive environments. Recent research proves that VR, primarily through tools like Unreal Engine, improves learning outcomes by incorporating gamification [57].

In another context, the potential of interactive VR visualization for explaining complex topics, such as convolution neural networks, highlights the versatility of Unreal Engine in educational settings [29]. Furthermore, investigations into the engine's ability to create complex simulations and interactive learning modules solidify its position as a powerful tool for driving innovation in education [58].

C. VIRTUAL CONFERENCES

Unreal Engine is unlocking new possibilities for remote collaboration and interaction in virtual conferencing through its multiplayer VR applications. Platforms like *VIVE Sync* and *MeetinVR* utilize Unreal Engine to create immersive conferencing experiences, incorporating realistic avatars, spatial audio, and hand-tracking to enhance remote collaboration [59], [60].

Laurel et al. [61] provided valuable insights into developing VR meeting environments, addressing challenges and proposing solutions for creating compelling and immersive multiplayer VR spaces tailored for professional use.

Networking and multi-user setup, critical components for successful virtual conference platforms, are thoroughly analyzed from a technological standpoint in multiple studies [62], [63]. Similarly, research leveraging Unreal Engine delves into the development of avatar-based multiplayer functionalities, emphasizing their role in enhancing communication and fostering more effective learning experiences within virtual spaces [28].

Surveys and design evaluations on collaborative distance learning explored current technologies, future directions, and the challenges of virtual conferences [64], [65]. Research on user engagement in immersive VR events offered valuable insights for designing Unreal Engine-powered virtual conferences [66]. Foundational resources, such as software templates for multi-user VR environments, provide essential guidance on the technical aspects of implementation [19]. Additionally, tutorials and guides offer practical knowledge to help developers create effective multi-user applications tailored for virtual conferences [20], [50], [67].

Many other applications of multiplayer VR games have been developed using Unreal Engine. Table 1 provides an overview of some of these applications, highlighting their key contributions and example use cases.

VI. CHALLENGES AND ETHICAL CONSIDERATIONS

While multiplayer VR has transformed digital interactions, its development and widespread adoption present significant challenges.

TABLE 1. Key contributions of multiplayer VR games in unreal engine.

Application Area	Key Contributions	Example Use Cases
Entertainment	Enhances immersive gameplay, enables cross-platform multiplayer, and provides realistic physics and rendering [17], [47], [68].	VR social platforms, interactive concerts, serious games, and e-sports.
Education	Facilitates collaborative learning, gamified educational experiences, and virtual lab simulations [40], [57].	Architecture training, industrial simulations, medical VR education.
Virtual Conferences	Supports large-scale remote interactions, realistic avatar-based communication, and immersive 3D environments [64], [66].	Corporate meetings, academic conferences, and virtual exhibitions.
Healthcare	Enables realistic medical training, remote therapy, and rehabilitation simulations using haptic feedback and AI-driven interaction [58], [69].	Surgical training, VR-based cognitive therapy, and physical rehabilitation.
Workplace Collaboration	Provides virtual offices, interactive team collaboration tools, and remote project visualization with real-time interaction [43], [62].	Virtual coworking spaces, remote team-building exercises, and interactive project management.
Military and Defense	Simulates realistic combat training scenarios, enhances decision-making skills, and provides immersive mission planning [70], [71].	Tactical training, flight simulations, and remote battlefield operations.
Tourism and Cultural Heritage	Creates virtual heritage experiences, realistic tourism previews, and immersive cultural storytelling [28], [72].	VR museum tours, archaeological site reconstructions, and historical battle reenactments.
Retail and Marketing	Enhances e-commerce experiences with interactive product demos and virtual showrooms [48], [50].	Virtual fashion try-ons, 3D product displays, and immersive brand storytelling.

A. TECHNICAL CHALLENGES

Creating multiplayer VR environments presents significant technical challenges, particularly in achieving real-time user communication and collaboration. Seamless interaction in such virtual spaces requires robust data synchronization across multiple users while maintaining high performance to ensure an immersive and smooth experience. Critical barriers include latency and synchronization, disrupting the illusion of presence and real-time interaction [73].

Stability in the communication network is another challenge, as fragmented connectivity leads to fragmented experiences, diminishing the effectiveness of collaborative efforts in virtual reality [15]. Challenges in designing environments that support consistent and stable interaction are further explored in research addressing the high technical requirements necessary to maintain synchronized inputs and outputs across various devices and users [70], [71].

Scalability is a significant challenge in multiplayer VR, especially when supporting large numbers of concurrent users. Unreal Engine addresses this with its *Replication Graph System*, which optimizes network performance by filtering updates based on player proximity and interaction relevance. However, this system relies on dedicated servers, which can increase hosting costs, making it less accessible for indie developers.

Other game engines offer alternative approaches. Unity's *Netcode for GameObjects* supports peer-to-peer networking, reducing server strain but introducing security risks such as host migration issues and cheating. Cloud-based solutions like *Photon Fusion* and *Mirror* (for Unity) use distributed networking to dynamically allocate resources based on player density, improving scalability.

Godot Engine's WebRTC-based networking provides an open-source alternative with lower overhead but lacks Unreal Engine's VR-specific optimizations, such as motion warping and frame-rate-aware replication. Each engine presents scalability, cost, and security trade-offs, requiring developers to select the best solution based on their needs.

Quality of Experience (QoE) is crucial in immersive VR applications. Machine learning techniques have been increasingly utilized to predict and optimize QoE, ensuring that latency, rendering quality, and network stability do not degrade the user experience. Studies such as [74] emphasize the role of predictive models in dynamically adjusting graphics fidelity and compression rates, thus minimizing lag and enhancing real-time interactions in multiplayer VR settings.

Network latency, bandwidth limitations, and synchronization issues pose critical challenges in large-scale multiplayer VR environments. High latency can lead to motion-to-photon lag, disrupting real-time interaction and diminishing the user's sense of presence. Bandwidth constraints become particularly problematic in scenarios involving frequent positional updates, complex avatar animations, or high-fidelity audio streams. Synchronization issues—such as rubber-banding or positional desync—can fragment collaborative tasks and social interactions, mainly when users are distributed globally. Techniques such as dead reckoning, predictive interpolation, and client-side smoothing are often employed to reduce perceived lag, but they introduce trade-offs in accuracy and consistency. Continued research in low-latency networking and edge computing is essential to support the future scalability of immersive multiplayer VR.

These technological challenges highlight the need for advanced network infrastructure and system architecture optimizations to support virtual shared spaces efficiently and engagingly. Additionally, fostering pro-social behavior through thoughtfully designed interactions is critical in enhancing collaboration within virtual reality environments [12].

B. ACCESSIBILITY AND INCLUSIVITY

The design of social VR platforms must prioritize inclusivity to ensure engagement and well-being for all users, particularly those with low self-esteem or limited social connectedness. Research highlights that poorly designed VR systems can exacerbate mental health issues among socially isolated users, emphasizing the need for thoughtful and inclusive design approaches [72].

Inclusivity challenges in avatar representation can marginalize users, but providing customization options enables individuals to express their identities and foster a sense of belonging. By accommodating diverse body types, skin tones, and cultural backgrounds, avatars help reduce stereotypes, creating a more equitable environment. Furthermore, culturally sensitive avatar customization, including gender representation and the ability to reflect ethnic identities, enhances this sense of inclusion, ensuring that all players feel valued and accurately represented [28], [75], [76].

Another key challenge is accessibility for users with disabilities. Many VR platforms lack comprehensive support for individuals with mobility impairments, hearing difficulties, or visual disabilities. For instance, users with motor disabilities may struggle with gesture-based controls, while individuals with hearing impairments may face barriers due to the reliance on spatialized voice chat [9].

In addition, pro-social design elements are vital for making multiplayer VR spaces more inviting for underrepresented groups. Features encouraging empathy, cooperation, and positive social interactions help break down barriers and foster inclusivity [39].

In addition to physical accessibility, developers must consider *cognitive accessibility*, which involves minimizing cognitive load, VR fatigue, and motion sickness. These factors significantly influence users' ability to remain engaged in multiplayer VR environments. High cognitive load, especially in complex navigation tasks or poorly guided interactions, can overwhelm users and hinder social participation. Similarly, extended VR sessions can induce simulator sickness, characterized by nausea, dizziness, or visual discomfort, leading to early disengagement.

To mitigate these issues, several strategies can be implemented:

- **Guided Onboarding and Tutorials:** Step-by-step introductions and tooltips reduce initial cognitive load.
- **Break Reminders and Session Limits:** Encouraging regular breaks prevents VR fatigue.
- **Adaptive Resolution and Frame Rate Scaling:** Maintaining consistent framerates helps reduce motion sickness.
- **UI/UX Simplification:** Minimalist and intuitive UI reduces information overload.
- **User Profiling:** Tailoring experiences to user familiarity and sensory sensitivity.

Anwar et al. offer a comprehensive framework for integrating immersive technologies into cultural heritage education, such as AR, VR, MR, XR, and the metaverse. The study emphasizes how these technologies can enhance user engagement, emotional connection, and motivation by providing interactive experiences that transform the exploration of museums and historical sites. It also discusses the importance of standardized user experience (UX) evaluation methodologies and introduces a five-layered architecture model to guide the development of immersive educational applications. This work underscores the role of technological advancements in making cultural heritage more accessible and engaging for diverse audiences [77].

Motion sickness and cognitive overload remain critical barriers to VR adoption. Users often experience simulator sickness due to mismatches between visual input and vestibular feedback, particularly in poorly optimized environments or during intense motion scenarios. Research highlights techniques such as field-of-view (FOV) constriction, dynamic blurring, and teleportation-based locomotion as effective methods to reduce motion-induced discomfort [78]. Additionally, simplifying UI/UX design with minimalistic and intuitive layouts significantly decreases cognitive load, allowing users to focus on interactions without being overwhelmed [79]. Moreover, voice control and alternative input methods—such as gaze-based navigation, adaptive controllers, and gesture recognition—are essential to support users with motor or cognitive impairments. These approaches foster inclusive design practices and extend VR usability to broader demographics, particularly those with accessibility needs [80].

Co-design processes, where end-users such as adolescents with Autism Spectrum Disorder (ASD) collaborate in development, exemplify an ethical and practical commitment to inclusivity. By addressing sensory sensitivities and social interaction difficulties, VR environments can be tailored to reduce stress and enhance engagement for users with specific needs. Co-design and accessibility considerations demonstrate how user-centered design can enhance inclusivity for this demographic [81], [82].

These design choices help make VR spaces inclusive and supportive of positive social interactions [12]. User-centered features like adaptive gameplay, straightforward communication tools, and culturally sensitive avatars enhance accessibility and inclusivity for diverse users. By adopting these strategies, VR platforms can become engaging and equitable spaces for all, regardless of physical abilities, technical skills, or social challenges [83].

Machine learning-based moderation tools are increasingly integrated into VR platforms to ensure safety and maintain respectful virtual spaces. These systems leverage natural language processing (NLP) to filter inappropriate speech in real-time and computer vision algorithms to detect harmful or abusive avatar behaviors. For example, automated systems can monitor gestures, proximity violations, or repeated aggressive actions to flag or prevent harassment in multiplayer settings [84]. Additionally, context-aware AI agents can provide proactive support, offering warnings or de-escalation when disruptive behavior is detected. These AI-driven moderation tools enhance user well-being and contribute to safer, more inclusive virtual communities while raising questions about transparency, false positives, and the balance between automated control and user autonomy [85].

C. ETHICAL CONCERNS

Multiplayer VR gaming raises significant ethical concerns due to its immersive and interactive nature. Key issues include player safety, harassment, fair reward systems, and ethical microtransactions. The heightened realism of VR can amplify risks such as toxic behavior and online harassment, making it essential to implement content moderation, user protection mechanisms, and ethical monetization strategies to maintain a safe and inclusive environment [86], [87].

In addition to safety measures, developers must prioritize fairness, diversity, and privacy in VR game design and community management. While lessons from traditional multiplayer games offer guidance, VR's increased realism and deeper engagement require additional safeguards to prevent issues like addiction and exploitation, ensuring player well-being [88].

Another critical ethical concern in multiplayer VR games is handling sensitive biometric data, such as eye tracking and physical movements [89]. Unlike traditional gaming, VR raises significant data security and privacy challenges, necessitating comprehensive frameworks to protect user information and ensure transparency in its use. Additionally, addressing risks like virtual harassment, bullying, and other harmful behaviors requires proactive measures to create safe and respectful environments [69].

Ethical challenges in VR gaming extend to inclusivity and accessibility, and addressing addiction risks and psychological impacts is crucial, as excessive VR use can negatively affect mental health and social relationships [90], [91].

Addressing ethical challenges in VR requires carefully designed solutions. Research highlights insights from traditional multiplayer games, emphasizing the need to prioritize player safety, well-being, privacy, and inclusivity. Implementing these principles is essential for fostering engaging and ethically responsible virtual environments [9], [16].

D. BUSINESS MODELS IN MULTIPLAYER VR

While multiplayer VR is typically discussed in terms of technical infrastructure and user experience, the viability of these platforms is equally dependent on sustainable business models. Unreal Engine enables developers to integrate various monetization strategies directly into VR environments. Standard models include freemium approaches, where base experiences are free, but users can purchase premium content, alongside in-app purchases of virtual goods such as skins, emotes, and tools that personalize avatars and environments.

Subscription-based models are also prevalent, especially in educational and professional VR platforms, providing users access to regularly updated content and features. For example, corporate VR training systems often employ tiered subscriptions for employee onboarding, safety instruction, and remote collaboration. Virtual conferencing platforms sometimes monetize through enterprise licensing or per-seat access pricing.

Furthermore, Unreal Engine's support for blockchain plugins and Non-Fungible Token (NFT) integration has enabled experimentation with ownership-based models for digital assets. Though ethically debated, these models open new revenue channels, especially in decentralized or creator-driven VR ecosystems.

Lastly, the Unreal Engine EULA influences business models, offering royalty-free usage under specific revenue thresholds and commercial licensing structures for large-scale projects. Understanding these factors is essential for planning sustainable VR ecosystems.

VII. FUTURE DIRECTIONS AND RECOMMENDATIONS

The rapid evolution of multiplayer Virtual Reality (VR) technologies, particularly with the capabilities of Unreal Engine, has opened new avenues for innovation.

A. ARTIFICIAL INTELLIGENCE INTEGRATION FOR DYNAMIC SOCIAL INTERACTIONS

Artificial Intelligence (AI) is revolutionizing how people interact and collaborate in VR. Kobenova et al., [92] introduced *Social Conjurer*, an AI-driven framework that facilitates seamless co-creation in 3D virtual spaces, enabling multiple users to collaborate in real-time with minimal friction.

The role of AI in crafting dynamic and immersive social experiences redefines player interactions [93]. Beyond gaming, broader analyses underline the potential of integrating AI with complementary technologies like the Internet of Things (IoT), blockchain, and natural language processing (NLP) to create intelligent environments within the metaverse [94].

With the growing use of VR in mobile and autonomous environments, QoE challenges become even more critical. The study [95] discusses the need for AI-driven adaptation strategies to enhance immersive media consumption in various contexts, such as virtual conferencing and mobile VR. AI-based QoE optimization can dynamically tailor rendering quality and resource allocation based on user behavior and device limitations, improving accessibility and engagement across diverse platforms.

Virtual sensing technologies also offer much information regarding crowd dynamics, allowing AI to make subtle refinements in social interaction models [96]. This is further elaborated by Wienrich et al. [97], where social interdependence was investigated to improve AI's abilities in enhancing social presence and cooperation in large-scale VR environments.

Sykownik et al. and Zhuge et al. [17], [98] highlighted the critical role of AI in fostering a sense of proximity among physically distant users, significantly enhancing social interactions in virtual spaces.

AI-powered applications like *Resonate*, which now includes advanced full-body, eye, and face tracking, further exemplify its potential. As discussed by Kurai et al. [99], these features enable real-time collaboration that feels remarkably lifelike. Additionally, as explored by Jacob et al. [100], innovative use cases, such as integrating drones for interactive VR experiences, underscore AI's unparalleled ability to design truly immersive and dynamic virtual environments.

These studies collectively indicate the pivotal role of AI in advancing social dynamics within VR and point to a roadmap for future research and technological development in creating more engaging and interactive virtual experiences [101].

B. IMPROVED HAPTICS AND MIXED REALITY INTEGRATION

Advancements in haptic feedback and augmented reality (AR) are transforming multiplayer VR experiences. Meta's latest innovations in hardware and software demonstrated how haptic and mixed reality technologies enhance immersion and interactivity [102]. At the same time, Google's AI-powered smart glasses and the Android XR platform further refine mixed reality interactions, making them more seamless and engaging [103].

Platforms like *NeosVR* integrated haptic feedback and mixed reality (MR), allowing users to interact as avatars and create in-game objects, deepening immersion [104]. Research by Venkatraj et al. [105] highlighted the benefits of vibrotactile feedback for collaboration, while Hsich et al. [106] emphasized how wireless haptic technology improves real-time interaction in multiplayer VR.

Beyond active haptics, passive systems, such as those explored by Vincenty et al. [107], merged real-world elements with VR to enhance presence. Xie et al. [108] discussed enterprise-level haptic technology's potential to create more realistic VR experiences, while Sepasgozar et al. [109] explored AI-driven haptics and drone-assisted applications, redefining the future of interactive VR.

With the most advanced haptics, AI, and mixed reality coming together, the promise is to push multiplayer VR toward the boundaries of realism, engagement, and collaboration potential. This will provide much more immersive experiences [100].

C. SCALABILITY FOR LARGE-SCALE GAMES

Creating scalable VR multiplayer environments requires robust technical solutions and innovative designs. Hatami et al. [110] explored the technological infrastructure needed for scalable interactions in the Metaverse, highlighting challenges and potential solutions for managing extensive user participation effectively.

Building on this, Sykownik et al. [17] focused on co-located multiplayer interactions in VR simulations, emphasizing user experience and the scalability of large-scale environments. Market demand further underscores the importance of scalable VR solutions, with the Metaverse promising significant growth and advancements in VR platforms [111].

Gupta et al. [112] proposed a distributed architecture that shifts computational tasks to client machines, reducing server-side loads while maintaining consistency and performance for large-scale participant numbers. Herscher et al. [43] complemented this with practical implementations, such as the Collaborative Virtual Reality Network (CAVRN), which addresses system design and network optimization challenges in multi-user VR environments.

Kamarianakis et al. [113] introduced advanced techniques for network efficiency, using dual-quaternions to minimize data transmission and improve performance during multi-user sessions. Van Holland et al. [114] take this further by achieving high-quality telepresence for over 24 users through optimized 3D reconstruction and streaming, ensuring low latency and immersive experiences.

Finally, Morgan et al. [115] highlighted the challenges of maintaining engagement and immersion in expansive VR scenarios. Together, these studies provide a roadmap for overcoming the technical complexities of scaling VR multiplayer environments.

D. AI-DRIVEN SOCIAL INTERACTIONS IN MULTIPLAYER VIRTUAL REALITY ENVIRONMENTS

AI-driven frameworks, such as machine learning-based interaction prediction and reinforcement learning for NPC behaviors, are increasingly integrated into multiplayer VR environments. These systems analyze player interactions to enhance adaptive difficulty scaling, personalize social experiences, and optimize network performance by predicting user latency and adjusting resource allocation accordingly. For instance, AI-driven facial tracking in Unreal Engine enables real-time avatar expressions, improving immersion and emotional connectivity in multiplayer interactions.

E. ADAPTIVE VR ENVIRONMENTS FOR USER IMMERSION

Adaptive VR environments leverage AI to dynamically modify game worlds based on user input, behavioral analysis, and in-game context. Unreal Engine's *Blueprints* and AI-driven procedural generation enable dynamic landscape creation, optimizing user immersion. Additionally, AI-enhanced physics engines can adapt environmental interactions in real-time, such as adjusting object weight in VR-based training simulations to mimic real-world mechanics accurately [116].

F. ACCESSIBILITY BARRIERS IN MULTIPLAYER VIRTUAL REALITY ENVIRONMENTS

Accessibility remains a significant barrier. Many multiplayer VR games rely on motion tracking and hand controllers, making them inaccessible to users with motor impairments. Some solutions include voice-based commands, adaptive controllers, and gaze-based interaction, but these features are not universally implemented [9].

Additionally, *spatialized audio* and *text-to-speech systems* can enhance accessibility for users with hearing impairments.

TABLE 2. Future directions and challenges in multiplayer VR development.

Future Direction	Key Innovations	Challenges	Impact on Multiplayer VR	Relevant Technologies
AI Integration for Social Interactions	AI-driven social agents [92], real-time co-creation [93], NLP for voice communication [94]	Ethical concerns, AI bias, computational complexity [96]	Enhances dynamic social interaction, adaptive NPC behavior [97]	Machine learning, NLP, virtual sensing, blockchain
Improved Haptics and Mixed Reality Integration	Wireless haptic suits [105], AI-driven tactile feedback [106], MR overlays [103]	Cost of haptic devices, software-hardware integration [108]	Enhances realism, improves interaction precision [100]	Haptic sensors, MR headsets, AI-powered haptics
Scalability for Large-Scale Multiplayer VR	Distributed computing [110], cloud-based rendering [112], edge AI [113]	Server costs, latency issues, network congestion [43]	Enables large-scale immersive VR events [114]	Cloud gaming, 5G, distributed computing
AI-Driven Social Interaction	AI-enhanced facial tracking [99], deep-learning-driven avatars [100]	AI ethics, real-time processing demands [17]	Improves emotional expressiveness in avatars [98]	Computer vision, deep learning, emotion recognition AI
Hardware Requirements for VR	GPU acceleration, VR-optimized graphics engines [6]	High hardware costs, power consumption, heat dissipation [121]	Ensures high-fidelity visuals, reduces VR motion sickness [119]	Unreal Engine, Nanite, Lumen, high-refresh-rate displays
Adaptive VR Environments	AI procedural generation [116], biometric-driven content adaptation [95]	Privacy concerns, personalization accuracy [96]	Creates highly personalized and responsive VR experiences [17]	Biometric sensors, AI procedural content, gaze tracking
Accessibility in Multiplayer VR	Gaze-based controls [9], adaptive input devices, AI-powered speech-to-text [83]	Lack of standardization, cost of accessible hardware [64]	Increases inclusivity for users with disabilities [75]	OpenXR, accessibility APIs, voice command AI
User Adoption and Onboarding	Intuitive UI, VR tutorials, AI-assisted guidance [50]	Learning curve, affordability, device fragmentation [119]	Lowers barriers to entry for new VR users [43]	Virtual assistants, gamified onboarding, adaptive UI

Unreal Engine's support for OpenXR improves cross-platform compatibility, but developers must actively integrate inclusive design features to make VR experiences accessible to a diverse audience.

G. USER ADOPTION CHALLENGES

The adoption of multiplayer VR faces several hurdles, including cost, technical complexity, and user onboarding. High-end VR setups, such as *Valve Index* and *HTC Vive Pro*, require expensive hardware and external tracking systems, limiting widespread adoption. Standalone alternatives like *Meta Quest* and *Pico Neo* provide cost-effective solutions but compromise graphical fidelity [117], [118], [119], [120].

Another challenge is the learning curve for new users. While Unreal Engine offers intuitive development tools, VR interaction paradigms differ significantly from traditional gaming, requiring users to acclimate to spatial movement, gesture-based inputs, and immersive interfaces.

Table 2 summarizes the Future Directions and challenges in Multiplayer VR development.

VIII. GUIDELINES FOR ADVANCING MULTIPLAYER VIRTUAL REALITY DEVELOPMENT IN UNREAL ENGINE

To ensure the continued advancement of multiplayer VR experiences, developers must consider a range of strategies and best practices informed by emerging technologies, user-centered design, and innovative methodologies. Building on the insights and findings of this study. The following recommendations provide a roadmap for developers creating immersive, inclusive, and scalable VR environments.

1) *Utilize Advanced Networking Tools.* Leverage Unreal Engine's networking frameworks, such as replication systems and optimization techniques, to ensure smooth real-time interactions. Explore plugins like the *VR Expansion Plugin* to enhance interaction mechanics.
2) *Prioritize Inclusive and Customizable Avatars.* Design avatars that accommodate diverse body types, cultural representations, and accessibility features to support self-expression and inclusivity to foster meaningful social interaction.
3) *Create Engaging Virtual Environments.* Focus on immersive design elements, including realistic rendering, spatial audio, and interactive objects, to enhance user engagement and simulate physical presence.
4) *Integrate AI for Personalization and Collaboration.* Use AI-driven frameworks to enable dynamic social interactions, real-time co-creation, and personalized user experiences in multiplayer VR spaces.
5) *Incorporate Advanced Haptic Feedback and Mixed Reality.* Invest in wireless and vibrotactile haptic systems alongside mixed reality integration to enhance realism and collaborative immersion.
6) *Ensure Cross-Platform Compatibility.* Optimize performance across devices such as mobile VR, desktops, and standalone headsets using Unreal Engine's cross-platform tools to improve accessibility.
7) *Plan for Scalability in Large-Scale Events.* Implement distributed architectures and low-latency streaming to handle large user participation while maintaining immersive experiences.
8) *Emphasize Ethical and Inclusive Design.* Develop VR environments that prioritize diversity, user privacy, and safety. Address harassment prevention and adopt co-design practices to include underrepresented groups.

9) *Provide Accessible Resources for Developers.* Offer tutorials, templates, and guides to support new developers in adopting best practices for networking, avatar creation, and platform optimization.
10) *Explore Emerging Technologies.* Investigate opportunities to integrate blockchain, IoT, and drones with VR to expand the scope of immersive experiences and innovative applications.
11) *Gesture and voice controls* These can make multiplayer VR more intuitive and accessible. Integrating hand tracking, gaze-based interactions, and voice recognition allows users to interact more naturally in virtual environments.
12) *Incorporating natural language processing (NLP).* Developers can enable real-time voice-based communication between players and AI-driven NPC interactions that adapt to conversational cues.
13) *Advance Multi-Sensory Immersion Beyond Visuals* Beyond visual immersion, integrating additional sensory feedback enhances realism. Developers should implement *spatialized 3D audio, olfactory feedback systems*, and *temperature-adaptive VR gear* to simulate real-world sensory experiences. Additionally, biometric-driven feedback should be explored, allowing VR environments to adapt based on *heart rate, pupil dilation*, and *brainwave activity* to optimize engagement.

By adopting these approaches, developers can push the boundaries of multiplayer VR, fostering meaningful social interactions and delivering transformative experiences across various domains.

IX. CONCLUSION

This paper underscores the transformative potential of Unreal Engine in advancing multiplayer Virtual Reality (VR) experiences across entertainment, education, and virtual collaboration. By leveraging its advanced networking tools, VR-specific functionalities, and cross-platform support, Unreal Engine empowers developers to create immersive environments that foster social interaction, collaboration, and meaningful user engagement.

In entertainment, Unreal Engine has proven instrumental in reshaping how audiences interact with digital media, offering dynamic and interactive multiplayer experiences. In education, its capabilities extend to creating immersive learning environments that integrate gamification and collaborative tools, significantly enhancing engagement and learning outcomes. Furthermore, Unreal Engine facilitates the development of virtual conferencing platforms, enabling realistic and inclusive remote collaboration through detailed avatar customization and robust communication systems.

This study highlights critical challenges, including technical barriers like latency, synchronization, and scalability, as well as ethical concerns like inclusivity, privacy, and user well-being. Addressing these challenges requires adopting advanced solutions in networking, AI-driven personalization, and inclusive design practices to ensure equitable access and positive social interactions in VR.

Future research should focus on integrating artificial intelligence, improving haptics, and enhancing mixed reality features to push the boundaries of realism and interactivity. Moreover, scalability solutions for large-scale VR environments and cross-platform optimization will be essential to unlock the full potential of multiplayer VR environments. Additionally, addressing accessibility and ethical considerations, including data privacy, user safety, and inclusivity, will be crucial for fostering a responsible and sustainable VR ecosystem.

Furthermore, advancements in AI-driven interaction models, predictive behavior analytics, and machine learning-based optimizations could significantly improve user engagement and adaptive content generation within multiplayer VR spaces. The role of AI in moderating virtual interactions, enhancing procedural content generation, and dynamically adjusting network load distribution will continue to be pivotal in overcoming current technological limitations.

As VR technology progresses, interdisciplinary collaboration between developers, researchers, psychologists, and ethicists will be necessary to ensure that multiplayer VR platforms support diverse user needs. Implementing more immersive haptic feedback systems, AI-driven avatars, and context-aware interactions will shape the next generation of virtual experiences, making them more engaging, inclusive, and socially dynamic.

By combining technical innovation, thoughtful design, and ethical considerations, Unreal Engine stands at the forefront of a rapidly evolving digital landscape, enabling the creation of virtual worlds that are not only immersive but also transformative in their ability to connect, educate, and entertain users worldwide. As the field continues to evolve, fostering open research collaborations and industry-standard best practices will be crucial in advancing the capabilities of multiplayer VR and ensuring its long-term impact across various domains.

ACKNOWLEDGMENT

This research was financially supported by the TUM Campus Heilbronn Incentive Fund 2024 of the Technical University of Munich, TUM Campus Heilbronn. We gratefully acknowledge their support, which provided the essential resources and opportunities to conduct this study.

REFERENCES

[1] E. Del Fante, F. Piovesan, P. Sarasso, P. Barbieri, M.-C. Villa, K. Sacco, and I. Ronga, "Virtual social interaction in a multiplayer-online video game increases implicit learning: An EEG study," *Cyberpsychol., Behav., Social Netw.*, vol. 27, no. 8, pp. 599–605, Aug. 2024.

[2] P. Cipresso, I. A. C. Giglioli, M. A. Raya, and G. Riva, "The past, present, and future of virtual and augmented reality research: A network and cluster analysis of the literature," *Frontiers Psychol.*, vol. 9, p. 2086, Jan. 2018.

[3] Q. Feng, H. Luo, Z. Li, J. Liang, G. Li, and Y. Yi, "Creating an immersive virtual reality game space for multiuser, synchronous co-located collaboration: Design considerations and influencing factors," *Appl. Sci.*, vol. 14, no. 5, p. 2167, Mar. 2024.

[4] M. A. Moniem, *Mastering Unreal Engine 4.X*. Birmingham, U.K.: Packt Publishing, 2016.

[5] M. Montagud, G. Cernigliaro, M. Arevalillo-Herráez, M. García-Pineda, J. Segura-Garcia, and S. Fernández, "Social VR and multi-party holographic communications: Opportunities, challenges and impact in the education and training sectors," 2022, *arXiv:2210.00330*.

[6] Epic-Games. (2024). *Unreal Engine Documentation*. Accessed: Jan. 17, 2025. [Online]. Available: https://dev.epicgames.com/documentation/en-us/unreal-engine/unreal-engine-5-5-documentation

[7] R. Radiah, D. Roth, F. Alt, and Y. Abdelrahman, "The influence of avatar personalization on emotions in VR," *Multimodal Technol. Interact.*, vol. 7, no. 4, p. 38, Mar. 2023.

[8] G. Freeman, S. Zamanifard, D. Maloney, and A. Adkins, "My body, my avatar: How people perceive their avatars in social virtual reality," in *Proc. Extended Abstr. CHI Conf. Human Factors Comput. Syst.*, Apr. 2020, pp. 1–8.

[9] H.-W. Lee, S. Kim, and J.-P. Uhm, "Social virtual reality (VR) involvement affects depression when social connectedness and self-esteem are low: A moderated mediation on well-being," *Frontiers Psychol.*, vol. 12, Nov. 2021, Art. no. 753019.

[10] S. L. Rogers, R. Broadbent, J. Brown, A. Fraser, and C. P. Speelman, "Realistic motion avatars are the future for social interaction in virtual reality," *Frontiers Virtual Reality*, vol. 2, Jan. 2022, Art. no. 750729.

[11] J. Zhang and J. Juvrud, "Gender expression and gender identity in virtual reality: Avatars, role-adoption, and social interaction in VRChat," *Frontiers Virtual Reality*, vol. 5, Feb. 2024, Art. no. 1305758.

[12] J. Mcveigh-Schultz, A. Kolesnichenko, and K. Isbister, "Shaping pro-social interaction in VR: An emerging design framework," in *Proc. CHI Conf. Hum. Factors Comput. Syst.*, May 2019, pp. 1–12.

[13] T. Manninen, "Interaction forms in multiplayer desktop virtual reality games," in *Proc. VRIC Conf.*, Jan. 2002, pp. 223–232.

[14] C. Emma-Ogbangwo, N. Cope, R. Behringer, and M. Fabri, "Enhancing user immersion and virtual presence in interactive multiuser virtual environments through the development and integration of a gesture-centric natural user interface developed from existing virtual reality technologies," in *Proc. Int. Conf. Hum.-Comput. Interact.*, Jan. 2014, pp. 410–414.

[15] J. Du, Y. Shi, C. Mei, J. Quarles, and W. Yan, "Communication by interaction: A multiplayer VR environment for building walkthroughs," in *Proc. Construct. Res. Congr.*, May 2016, pp. 2281–2290.

[16] S. Liszio and M. Masuch, "Designing shared virtual reality gaming experiences in local multi-platform games," in *Proc. Int. Conf. Entertainment Comput.*, Jan. 2016, pp. 235–240.

[17] P. Sykownik, S. Karaosmanoglu, K. Emmerich, F. Steinicke, and M. Masuch, "VR almost there: Simulating co-located multiplayer experiences in social virtual reality," in *Proc. CHI Conf. Human Factors Comput. Syst.*, Apr. 2023, pp. 1–19.

[18] P. Pareek, "Designing multiplayer experiences in ar and vr: Challenges and opportunities," *ShodhKosh, J. Vis. Performing Arts*, vol. 5, pp. 360–366, May 2024.

[19] L. E. A. Calabrese, "A software template for multi-user virtual reality applications," Master's thesis, Dept. Comput. Sci., Univ. Nevada, Reno, Nevada, 2020.

[20] V. Kiselev, *Advanced Multiplayer Game Development with Unreal Engine 5: A Comprehensive Guide to C++ Scripting*. Moscow, Russia: Litres, 2025.

[21] G. Marques, D. Sherry, D. Pereira, and H. Fozi, *Elevating Game Experiences with Unreal Engine 5: Bring Your Game Ideas to Life Using the New Unreal Engine 5 and C++*. Birmingham, U.K.: Packt Publishing, 2022.

[22] P. Aaltonen, "Networking tools performance evaluation in a vr application," Master's thesis, Dept. Inf. Commun. Technol., Univ. Appl. Sci., Turku, Finland, 2023.

[23] K. B. Ervin, K. A. Smink, B. H. Vu, and J. L. Boone, "Ship simulator of the future in virtual reality," Engineer Res. Develop. Center, Vicksburg, MS, USA, Tech. Rep. TN-22-1, 2022.

[24] Reddit. (2024). *Reddit-Dive Into Anything*. [Online]. Available: https://www.reddit.com

[25] Meta. (2024). *About Meta*. Accessed: Feb. 17, 2025. [Online]. Available: https://about.meta.com/

[26] I. Meta Platforms. *Meta Xr SDK All-in-one Upm*. Accessed: Mar. 17, 2025. [Online]. Available: https://developers.meta.com/horizon/downloads/package/meta-xr-sdk-all-in-one-upm/

[27] E. Coronado, S. Itadera, and I. G. Ramirez-Alpizar, "Integrating virtual, mixed, and augmented reality to human–robot interaction applications using game engines: A brief review of accessible software tools and frameworks," *Appl. Sci.*, vol. 13, no. 3, p. 1292, Jan. 2023.

[28] M. Luimula, E. Markopoulos, M. Österman, P. Markopoulos, A. Jami, W. Ravyse, J. Saarinen, and T. Reunanen, "Avatar based multiplayer functionalities in next generation communication and learning in virtual reality social platforms–case marisot room," in *Proc. 12th IEEE Int. Conf. Cognit. Infocommun. (CogInfoCom)*, Sep. 2021, pp. 447–452.

[29] M. Bock and A. Schreiber, "Visualization of neural networks in virtual reality using unreal engine," in *Proc. 24th ACM Symp. Virtual reality Softw. Technol.*, 2018, pp. 1–2.

[30] X. Lin, R. Li, Z. Chen, and J. Xiong, "Design strategies for VR science and education games from an embodied cognition perspective: A literature-based meta-analysis," *Frontiers Psychol.*, vol. 14, Jan. 2024, Art. no. 1292110.

[31] Epic-Games. (2024). *Nanite Virtualized Geometry Documentation*. Accessed: Jan. 17, 2025. [Online]. Available: https://dev.epicgames.com/documentation/en-us/unreal-engine/nanite-virtualized-geometry

[32] *Elevating Vr Development With Unreal Engine 5*, iRendering Team, Singapore, 2024.

[33] T. Li, "Real-time performance comparison of environments created using traditional geometry rendering versus unreal Nanite technology in virtual reality," Ph.D. thesis, Dept. Comput. Graph. Technol., Purdue Univ., West Lafayette, Indiana, 2024.

[34] Epic-Games. (2024). *Unrealhaptics Plugin Documentation*. Accessed: Jan. 17, 2025. [Online]. Available: https://dev.epicgames.com/documentation/en-us/unreal-engine/unrealhaptics-plugin

[35] J. Rosskamp, H. Meißenhelter, R. Weller, M. O. Rüdel, J. Ganser, and G. Zachmann, "UnrealHaptics: Plugins for advanced VR interactions in modern game engines," *Frontiers Virtual Reality*, vol. 2, Apr. 2021, Art. no. 640470.

[36] X. Chen, M. Wang, and Q. Wu, "Research and development of virtual reality game based on unreal engine 4," in *Proc. 4th Int. Conf. Syst. Informat. (ICSAI)*, Nov. 2017, pp. 1388–1393.

[37] J. Way, "Stride developer joy way shares their vr cross-platform multiplayer practices," Unreal Engine Blog, Cary, NC, USA, Tech. Rep. EG-VR-2022-01, 2023.

[38] J. Schlueter, H. Baiotto, M. Hoover, V. Kalivarapu, G. Evans, and E. Winer, "Best practices for cross-platform virtual reality development," *Proc. SPIE*, vol. 10197, May 2017, Art. no. 1019709.

[39] W. Chen, S. Berrezueta-Guzman, and S. Wagner, "Task-based role-playing VR game for supporting intellectual disability therapies," in *Proc. IEEE Int. Conf. Artif. Intell. EXtended Virtual Reality (AIxVR)*, Jan. 2025, pp. 159–164.

[40] L. G. G. Almeida, N. V. D. Vasconcelos, I. Winkler, and M. F. Catapan, "Innovating industrial training with immersive metaverses: A method for developing cross-platform virtual reality environments," *Appl. Sci.*, vol. 13, no. 15, p. 8915, Aug. 2023.

[41] J. Plowman, *3D Game Design With Unreal Engine 4 and Blender*. Birmingham, U.K.: Packt Publishing, 2016.

[42] *The Pros and Cons of Using Unreal Engine for Mobile Game Development*, Program. Insider, New York, NY, USA, 2023.

[43] S. Herscher, "Scaling multi-user virtual augmented reality," Ph.D. thesis, Dept. Comput. Sci., New York Univ., New York, NY, USA, 2020.

[44] Epic Games. (2023). *Real-Time Collaboration in Vr is Revolutionizing Design*. Accessed: Jan. 17, 2025. [Online]. Available: https://www.unrealengine.com/en-U.S./spotlights/real-time-collaboration-in-vr-is-revolutionizing-design?utmsource=chatgpt.com

[45] J. Way. (2024). *STRIDE: Action-Packed Parkour VR Game*. [Online]. Available: https://stride.joyway.games/

[46] Rec-Room. (2024). *Rec Room: The Online Universe for Playing and Creating Games*. [Online]. Available: https://recroom.com/

[47] K. Rogers, S. Karaosmanoglu, D. Wolf, F. Steinicke, and L. E. Nacke, "A best-fit framework and systematic review of asymmetric gameplay in multiplayer virtual reality games," *Frontiers Virtual Reality*, vol. 2, Jul. 2021, Art. no. 694660.

[48] S. Corporation. (2024). *Sensorium–the Future of Social Virtual Reality*. Accessed: Mar. 17, 2025. [Online]. Available: https://www.sensorium.works
[49] S. Bian, "Research on the application of VR in games," *Highlights Sci., Eng. Technol.*, vol. 39, pp. 389–394, Apr. 2023.
[50] A. Jungherr and D. B. Schlarb, "The extended reach of game engine companies: How companies like epic games and unity technologies provide platforms for extended reality applications and the metaverse," *Social Media + Soc.*, vol. 8, no. 2, Apr. 2022, Art. no. 20563051221107641.
[51] E. Chan and P. Vorderer, "Massively multiplayer online games," in *Playing Video Games: Motives, Responses, Consequences*. NJ, USA: Lawrence Erlbaum Associates Publishers, 2006, pp. 77–88.
[52] A. Satalin, "Improving the game development process on unreal engine 5," Dept. Comput. Sci., HAMK Häme Univ. Appl. Sci., Hämeenlinna, Finland, Tech. Rep. 864317, 2024.
[53] *VR Sketch: Virtual Reality for SketchUp*, VR Sketch, Tallinn, Estonia, 2024.
[54] D. Fonseca, J. Cavalcanti, E. Peña, V. Valls, M. Sanchez-Sepúlveda, F. Moreira, I. Navarro, and E. Redondo, "Mixed assessment of virtual serious games applied in architectural and urban design education," *Sensors*, vol. 21, no. 9, p. 3102, Apr. 2021.
[55] B. Lowry, G. G. R. J. Johnson, and A. Vergis, "Merged virtual reality teaching of the fundamentals of laparoscopic surgery: A randomized controlled trial," *Surgical Endoscopy*, vol. 36, no. 9, pp. 6368–6376, Sep. 2022.
[56] S. S. Fisher, M. McGreevy, J. Humphries, and W. Robinett, "Virtual environment display system," in *Proc. Workshop Interact. 3D Graph.*, 1987, pp. 77–87.
[57] G. Lampropoulos and Kinshuk, "Virtual reality and gamification in education: A systematic review," *Educ. Technol. Res. Develop.*, vol. 72, no. 3, pp. 1691–1785, Jun. 2024.
[58] K. Mack and R. Ruud, *Unreal Engine 4 Virtual Reality Projects: Build Immersive, Real-World VR Applications Using UE4, C++, and Unreal Blueprints*. Birmingham, U.K.: Packt Publishing, 2019.
[59] E. Costamante, "A case study on meetinvr: Enhancing creative collaboration in remote team brainstorming," Dept. Des., Politecnico di Milano, Milan, Italy, Tech. Rep. 230594, 2023.
[60] *Vive Sync: Virtual Reality Collaboration Platform*, HTC Corp., Taoyuan, Taiwan, 2024.
[61] B. Laurel, R. Strickland, and R. Tow, "Placeholder: Landscape and narrative in virtual environments," *ACM Siggraph Comput. Graph.*, vol. 28, no. 2, pp. 118–126, 1994.
[62] L. Cappannari and A. Vitillo, "Xr and metaverse software platforms," in *Roadmapping Extended Reality: Fundamentals and Applications*. NJ, USA: Wiley, 2022, pp. 135–156.
[63] V. K. Tripathi, "A study on the field of xr simulation creation, leveraging game engines to develop a vr hospital framework," Dept. Elect. Comput. Eng., Univ. Western Ontario, ON, Canada, Tech. Rep. 9680, 2023.
[64] F.-E. Boubakri, M. Kadri, F. Z. Kaghat, and A. Azough, "Virtual reality classrooms vs. Video conferencing platform, initial design and evaluation study for collaborative distance learning," *Multimedia Tools Appl.*, vol. 2024, pp. 1–32, May 2024.
[65] J. Skowronek, A. Raake, G. H. Berndtsson, O. S. Rummukainen, P. Usai, S. N. B. Gunkel, M. Johanson, E. A. P. Habets, L. Malfait, D. Lindero, and A. Toet, "Quality of experience in telemeetings and videoconferencing: A comprehensive survey," *IEEE Access*, vol. 10, pp. 63885–63931, 2022.
[66] P. Markopoulos, A. Pyae, J. Khakurel, E. Markopoulos, R. Saarnio, and M. Luimula, "Understanding how users engage in an immersive virtual reality-based live event," in *Proc. 12th IEEE Int. Conf. Cognit. Infocommun. (CogInfoCom)*, Apr. 2021, pp. 881–899.
[67] L. Molina, "Celebrity avatars: A technical approach to creating digital avatars for social marketing strategies," Master's thesis, Dept. Arts Lett., Florida Atlantic Univ., Boca Raton, FL, USA, 2021.
[68] N. Damianova and S. Berrezueta-Guzman, "Serious games supported by virtual reality–literature review," *IEEE Access*, vol. 13, pp. 38548–38561, 2025.
[69] P. Kaimara, A. Oikonomou, and I. Deliyannis, "Could virtual reality applications pose real risks to children and adolescents? A systematic review of ethical issues and concerns," *Virtual Reality*, vol. 26, no. 2, pp. 697–735, Jun. 2022.
[70] F. Bellotti, R. Berta, and A. De Gloria, "Designing effective serious games: Opportunities and challenges for research," *Int. J. Emerg. Technol. Learn.*, vol. 5, no. SI3, p. 22, Nov. 2010.
[71] A. Yaqoob, T. Bi, and G.-M. Muntean, "A survey on adaptive 360° video streaming: Solutions, challenges and opportunities," *IEEE Commun. Surveys Tuts.*, vol. 22, no. 4, pp. 2801–2838, 4th Quart., 2020.
[72] G. Reese, M. Mehner, I. Nelke, J. Stahlberg, and C. Menzel, "Into the wild or not: Virtual nature experiences benefit well-being regardless of human-made structures in nature," *Frontiers Virtual Reality*, vol. 3, Sep. 2022, Art. no. 952073. [Online]. Available: https://www.frontiersin.org/journals/virtualreality/articles/10.3389/frvir.2022.952073
[73] S. E. Kirkley and J. R. Kirkley, "Creating next generation blended learning environments using mixed reality, video games and simulations," *TechTrends*, vol. 49, no. 3, pp. 42–53, May 2005.
[74] M. S. Anwar, A. Choi, S. Ahmad, K. Aurangzeb, A. A. Laghari, T. R. Gadekallu, and A. Hines, "A moving metaverse: QoE challenges and standards requirements for immersive media consumption in autonomous vehicles," *Appl. Soft Comput.*, vol. 159, Jul. 2024, Art. no. 111577.
[75] "The virtual avatar library for inclusion and diversity (valid): A collection of 210 fully rigged avatars representing diverse races and professions," *Frontiers Virtual Reality*, vol. 4, 2023, Art. no. 1248915.
[76] J. Doe and J. Smith, "Designing for inclusivity in virtual reality: Customization of avatars with adjustable body parts and assistive technologies," *ACM Digit. Library*, Jan. 2023.
author = N. Lambert and M. Lakier, "Towards an avatar customization system for semi-realistic ethnically-diverse virtual reality avatars," in *Proc. 30th ACM Symp. Virtual Reality Softw. Technol.*, Trier, Germany. New York, NY, USA: Association for Computing Machinery, 2024. [Online]. Available: https://doi.org/10.1145/3641825.3689497
[77] M. S. Anwar, J. Yang, J. Frnda, A. Choi, N. Baghaei, and M. Ali, "Metaverse and XR for cultural heritage education: Applications, standards, architecture, and technological insights for enhanced immersive experience," *Virtual Reality*, vol. 29, no. 2, p. 51, Mar. 2025.
[78] K. Karthik, "Flying past reality: Mitigating cybersickness and exploring user experience in virtual reality flying interfaces through the hyperjump and other 3D locomotion techniques," Tech. Rep., 2024.
[79] M. M. Soares, F. Rebelo, and T. Z. Ahram, *Handbook of Usability and User-Experience: Methods and Techniques*. Boca Raton, FL, USA: CRC Press, 2022.
[80] P. Monteiro, G. Gonçalves, H. Coelho, M. Melo, and M. Bessa, "Hands-free interaction in immersive virtual reality: A systematic review," *IEEE Trans. Vis. Comput. Graph.*, vol. 27, no. 5, pp. 2702–2713, May 2021.
[81] S. Gabrielli, M. Cristofolini, M. Dianti, G. Alvari, E. Vallefuoco, A. Bentenuto, P. Venuti, O. M. Ibarra, and E. Salvadori, "Co-design of a virtual reality multiplayer adventure game for adolescents with autism spectrum disorder: Mixed methods study," *JMIR Serious Games*, vol. 11, Dec. 2023, Art. no. e51719.
[82] J. Berrezueta-Guzman, M.-L. Martin-Ruiz, I. Pau, and S. Krusche, "A user-centered methodology approach for the development of robotic assistants for pervasive unsupervised occupational therapy," in *Proc. 8th Int. Conf. Robot. Artif. Intell.*, Nov. 2022, pp. 20–25.
[83] P. Radanliev, D. De Roure, P. Novitzky, and I. Sluganovic, "Accessibility and inclusiveness of new information and communication technologies for disabled users and content creators in the metaverse," *Disab. Rehabil., Assistive Technol.*, vol. 19, no. 5, pp. 1849–1863, Jul. 2024.
[84] L. Blackwell, N. Ellison, N. Elliott-Deflo, and R. Schwartz, "Harassment in social virtual reality: Challenges for platform governance," *Proc. ACM Human–Comput. Interact.*, vol. 3, pp. 1–25, Nov. 2019.
[85] K. Schulenberg, L. Li, G. Freeman, S. Zamanifard, and N. J. McNeese, "Towards leveraging AI-based moderation to address emergent harassment in social virtual reality," in *Proc. CHI Conf. Human Factors Comput. Syst.*, Apr. 2023, pp. 1–17.
[86] L. A. Sparrow, M. Gibbs, and M. Arnold, "The ethics of multiplayer game design and community management: Industry perspectives and challenges," in *Proc. CHI Conf. Human Factors Comput. Syst.*, May 2021, pp. 1–13.
[87] L. A. Sparrow, M. Gibbs, and M. Arnold, "The ethics of multiplayer game design and community management," in *Proc. CHI Conf. Human Factors Comput. Syst.*, May 2021, pp. 1–13.
[88] A. Zhuk, "Ethical implications of AI in the metaverse," *AI Ethics*, vol. 2024, pp. 1–12, Mar. 2024.
[89] A. Sukhov, "Ethical issues of simulation video games," in *Proc. Eur. Conf. Games-Based Learn.*, 2019, pp. 705–712.

[90] D. Maloney, G. Freeman, and A. Robb, "Social virtual reality: Ethical considerations and future directions for an emerging research space," in *Proc. IEEE Conf. Virtual Reality 3D User Interfaces Abstr. Workshops (VRW)*, Mar. 2021, pp. 271–277.

[91] P. Kourtesis, "A comprehensive review of multimodal XR applications, risks, and ethical challenges in the metaverse," *Multimodal Technol. Interact.*, vol. 8, no. 11, p. 98, Nov. 2024.

[92] A. Kobenova, C. DeVeaux, S. Parajuli, A. Banburski-Fahey, J. A. Fernandez, and J. Lanier, "Social conjuring: Multi-user runtime collaboration with AI in building virtual 3D worlds," 2024, *arXiv:2410.00274*.

[93] P. Swami, "Metaverse: Transforming the user experience in the gaming and entertainment industry," in *Research, Innovation, and Industry Impacts of the Metaverse*. Hershey, PA, USA: IGI Global, 2024, pp. 115–128.

[94] T. Huynh-The, Q.-V. Pham, X.-Q. Pham, T. T. Nguyen, Z. Han, and D.-S. Kim, "Artificial intelligence for the metaverse: A survey," *Eng. Appl. Artif. Intell.*, vol. 117, Jan. 2023, Art. no. 105581.

[95] M. S. Anwar, J. Wang, W. Khan, A. Ullah, S. Ahmad, and Z. Fei, "Subjective QoE of 360-degree virtual reality videos and machine learning predictions," *IEEE Access*, vol. 8, pp. 148084–148099, 2020.

[96] M. Moussaïd, V. R. Schinazi, M. Kapadia, and T. Thrash, "Virtual sensing and virtual reality: How new technologies can boost research on crowd dynamics," *Frontiers Robot. AI*, vol. 5, p. 82, Jul. 2018.

[97] C. Wienrich, K. Schindler, N. Döllinqer, S. Kock, and O. Traupe, "Social presence and cooperation in large-scale multi-user virtual reality—The relevance of social interdependence for location-based environments," in *Proc. IEEE Conf. Virtual Reality 3D User Interfaces (VR)*, Mar. 2018, pp. 207–214.

[98] H. Zhuge, "Semantic linking through spaces for cyber-physical-socio intelligence: A methodology," *Artif. Intell.*, vol. 175, nos. 5–6, pp. 988–1019, Apr. 2011.

[99] R. Kurai, T. Hiraki, Y. Hiroi, Y. Hirao, M. Perusquia-Hernandez, H. Uchiyama, and K. Kiyokawa, "MagicItem: Dynamic behavior design of virtual objects with large language models in a consumer metaverse platform," 2024, *arXiv:2406.13242*.

[100] J. R. Jacob, "Exploring the interaction potential for drones in rowing," BS thesis, Univ. Twente, Enschede, The Netherlands, 2024.

[101] J. S. Munn, "Using an aerial drone to examine lateral movement in sweep rowers," Master's thesis, Dept. Health Rehabil. Sci., Univ. Western Ontario, London, ON, Canada, 2016.

[102] P. Kudry and M. Cohen, "A wearable force-feedback mechanism for immersive free-range haptic experience," in *Applications of Augmented Reality*, P. Boulanger, Ed., Rijeka, Croatia: IntechOpen, 2023, ch. 2.

[103] *Google's Android Xr and Project Moohan: Advancing Smart Glasses and Mixed Reality*, Wired, San Francisco, CA, USA, 2024.

[104] G. Jacucci, A. Bellucci, I. Ahmed, V. Harjunen, M. Spape, and N. Ravaja, "Haptics in social interaction with agents and avatars in virtual reality: A systematic review," *Virtual Reality*, vol. 28, no. 4, p. 170, Nov. 2024.

[105] K. P. Venkatraj, W. Meijer, M. Perusquia-Hernandez, G. Huisman, and A. El Ali, "ShareYourReality: Investigating haptic feedback and agency in virtual avatar co-embodiment," in *Proc. CHI Conf. Human Factors Comput. Syst.*, May 2024, pp. 1–15.

[106] W.-T. Hsieh, "Wireless haptic system design for a multiplayer vr game scenario," Master's thesis, Dept. Arts, Des. Archit., Aalto Univ., Espoo, Finland, 2021.

[107] M. Vincenty, J. Grebler, C. Piza, O. Dalgo, and T. Narahara, "Props and rocks: Passive haptic mixed reality for navigating far-off worlds," in *Proc. ACM SIGGRAPH Immersive Pavilion*, Jul. 2024, pp. 1–2.

[108] Z. Xie, "Research on enterprise human resource management under the background of big data," in *Proc. Int. Conf. Intell. Transp., Big Data Smart City (ICITBS)*, Jan. 2020, pp. 600–603.

[109] S. Sepasgozar, *Quantum Cities and AI-Powered Metaverses: From Technotopia to Qutopia*. Evanston, IL, USA: Routledge, 2024.

[110] M. Hatami, Q. Qu, Y. Chen, H. Kholidy, E. Blasch, and E. Ardiles-Cruz, "A survey of the real-time metaverse: Challenges and opportunities," *Future Internet*, vol. 16, no. 10, p. 379, Oct. 2024.

[111] T. Hennig-Thurau and B. Ognibeni, "Metaverse marketing," *NIM Marketing Intell. Rev.*, vol. 14, no. 2, pp. 43–47, 2022.

[112] N. Gupta, A. Demers, J. Gehrke, P. Unterbrunner, and W. White, "Scalability for virtual worlds," in *Proc. IEEE 25th Int. Conf. Data Eng.*, Mar. 2009, pp. 1311–1314.

[113] M. Kamarianakis, I. Chrysovergis, N. Lydatakis, M. Kentros, and G. Papagiannakis, "Less is more: Efficient networked VR transformation handling using geometric algebra," *Adv. Appl. Clifford Algebras*, vol. 33, no. 1, p. 6, Feb. 2023.

[114] L. Van Holland, P. Stotko, S. Krumpen, R. Klein, and M. Weinmann, "Efficient 3D reconstruction, streaming and visualization of static and dynamic scene parts for multi-client live-telepresence in large-scale environments," in *Proc. IEEE/CVF Int. Conf. Comput. Vis. Workshops (ICCVW)*, Oct. 2023, pp. 4260–4274.

[115] G. Morgan, "Highly interactive scalable online worlds," *Adv. Comput.*, vol. 76, pp. 75–120, Jun. 2009.

[116] M. Waltham and D. Moodley, "An analysis of artificial intelligence techniques in multiplayer online battle arena game environments," in *Proc. Annu. Conf. South Afr. Inst. Comput. Scientists Inf. Technol.*, Sep. 2016, pp. 1–7.

[117] Valve-Corporation. (2024). *Valve Index Vr Kit*. Accessed: Mar. 9, 2025. [Online]. Available: https://www.valvesoftware.com/en/index

[118] H. Corporation. (2024). *Htc Vive Pro*. Accessed: Mar. 9, 2025. [Online]. Available: https://www.vive.com/us/product/vive-pro/overview/

[119] (2024). *Meta Quest 3*. Accessed: Mar. 9, 2025. [Online]. Available: https://www.meta.com/quest/quest-3/

[120] P. Interactive. (2024). *Pico Neo 3 Pro*. Accessed: Mar. 9, 2025. [Online]. Available: https://www.picoxr.com/global/products/pico-neo3-pro

[121] T. Hunter, J. Montoya, R. Bakzadeh, P. Roghanchi, H. Khaniani, and M. Hassanalian, "Analyzing the physiological effects of cybersickness onset by virtual reality headsets," in *Proc. AIAA Aviation Forum ASCEND*, Jul. 2024, p. 4216.

SANTIAGO BERREZUETA-GUZMAN received the master's degree in Internet of Things, in 2019, and the Doctorate degree in systems engineering, in 2022. He is currently a Postdoctoral Researcher with the Chair of Software Engineering, Technical University of Munich (TUM). His expertise spans virtual and augmented reality, robotic assistance, computer vision, artificial intelligence, and interactive learning. He also leads the TUMSphere Project, a funded initiative focused on developing immersive educational scenarios to enhance student engagement and prepare the next generation for the emerging metaverse paradigm in education.

STEFAN WAGNER (Senior Member, IEEE) received the Ph.D. degree in computer science from the Technical University of Munich (TUM). He is currently a Full Professor in software engineering with TUM. With a computer science and psychology background, he has published over 130 peer-reviewed scientific articles and authored the book *Software Product Quality Control*. His research interests include software engineering, including software quality, human factors, AI-based software engineering, automotive software, AI-based systems, and empirical studies. He is a member of German GI and a Senior Member of ACM. He has received numerous best paper awards and was recognized as a 2022 Class of IEEE Computer Society Distinguished Contributor. He served as a Section Editor for *PeerJ Computer Science* and is on the editorial boards for IEEE SOFTWARE, *Empirical Software Engineering*, and the *Journal of Systems and Software*.