Baltic J. Modern Computing, Vol. 14 (2026), No. 1, pp. 1–26
https://doi.org/10.22364/bjmc.2026.14.1.01

Immersive Virtual Environments in Higher Education: An Open-Source 3D World Adaptation Using Oculus Meta Quest

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Abstract. Virtual reality (VR) has become a key tool in education, although some students still struggle with focus, leading to high dropout rates. The goal of this research was to create a more engaging and effective learning environment through immersive technology, but high costs remain a barrier for low-budget educational institutions. This study evaluates the implementation of an open-source immersive VR (IVR) solution for education, combining OpenSimulator, Firestorm VR, SteamVR and Meta Quest 2, as a cost-effective alternative to commercial platforms. Through systematic hardware benchmarking, we demonstrate a cost reduction compared to commercial solutions while maintaining high performance through optimized hardware configurations. Comparative analysis reveals that open-source solutions offer superior customization and privacy control, although they require greater technical experience for implementation. These findings provide actionable guidelines for institutions adopting IVR, balancing performance and affordability.

Keywords: Immersive virtual reality, Metaverse, Meta Quest 2, OpenSimulator, Open-source, 3D virtual world

1 Introduction

Current education systems confront significant challenges to keep students engaged in digital learning spaces, leading many institutions to explore immersive technologies like VR. Although VR shows great promise for creating interactive educational experiences, high costs make it difficult for most institutions to implement. Studies show that bringing VR into classrooms requires expensive equipment, specialized software, and teacher training (Radianti et al., 2020). This creates an unfair situation where only well-funded institutions can afford these advanced tools, while others fall further behind, a pattern that research confirms widens existing educational gaps (Pellas et al., 2021).

A significant factor behind the growing interest in immersive technologies is the evolving profile of today's learners. Empirical evidence shows that contemporary students tend to exhibit shorter attention spans, stronger preference for active learning, and higher expectations for interactive digital environments (Makransky and Lilleholt, 2018 ; Parong and Mayer, 2018). Traditional 2D interfaces often fail to provide the level of engagement required to maintain attention and promote deep learning. In contrast, immersive VR (IVR) enhances presence, embodiment, and cognitive focus, offering a promising alternative for addressing attention-related disengagement.

Open-source 3D virtual world such as OpenSimulator represent an opportunity for higher education institutions seeking to adopt immersive technologies without the prohibitive costs typically associated with commercial IVR platforms. These environments allow the creation of large-scale, customizable virtual campuses that can be accessed with low-cost consumer-grade VR headsets.

Despite the potential of IVR technologies, previous research has rarely addressed how institutions with restricted budgets can transition from conventional 2D/3D platforms to fully immersive environments. We examine not only the pedagogical benefits of IVR but also the economic and technical feasibility of deploying open-source VR solutions in resource-constrained institutions.

This work proposes a methodological framework for transitioning from non-immersive and semi-immersive systems to fully immersive virtual reality environments using open-source tools (OpenSimulator, Firestorm VR) and affordable hardware (Meta Quest 2). The framework includes benchmarking of performance parameters, evaluation of cost - effectiveness, and identification of minimum hardware specifications required to ensure fluid and comfortable immersive experiences.

In summary, this study aims to provide a replicable roadmap for higher education institutions to adopt IVR environments using open-source technologies, while addressing three key dimensions: (1) pedagogical alignment with current learner needs, (2) technical performance and hardware feasibility, and (3) cost-effectiveness supported by pricing sources. This approach positions the research as a practical and equitable solution for institutions seeking to modernize their digital learning ecosystems under financial constraints.

1.1 Non-immersive virtual reality to immersive virtual reality

Due to technological limitations and high costs, VR was largely confined to specialized fields such as medical simulation, flight simulators, and industrial design, making it inaccessible to most people. Attempts to popularize VR in the 1990s, such as Nintendo's

Virtual Boy and Sega's VR, ended in commercial failure. However, recent advances in mobile and wearable technologies, now more accessible and affordable, have brought us to what some consider a defining moment for VR (Huggett, 2020).

VR is a technology designed to transport users into digitally constructed environments, commonly referred to as the metaverse. This technology creates a compelling sense of physical presence, defined as the psychological perception of 'being there' within a computer simulated space (Lyu et al., 2023). VR achieves this through experiential interaction with simulated environments, that replicate physical reality using specialized interfaces, including head-mounted displays (HMDs), motion controllers, and haptic feedback systems (Fusaro, 2025). VR systems can be categorized into three distinct modalities based on immersion levels: non-immersive, semi-immersive, and immersive (Fig. 1) (Salatino et al., 2023). Non-immersive, the most basic form, utilizes standard desktop computers where users observe virtual environments through a screen interface and interact via traditional input devices like keyboards or mouse, an approach that generally offers limited user engagement. Semi-immersive systems represent an intermediate level, employing advanced graphics workstations to deliver enhanced spatial presence while maintaining some connection to the physical environment. The highest level, fully immersive, provides complete environmental engagement through HMDs or similar head-coupled devices, creating the most authentic simulation of virtual spaces by surrounding the user's visual field and tracking head movements in real-time. (Ibrahim and Juhari, 2019; Salatino et al., 2023; Stracke et al., 2025). Fully immersive systems also enable spatial and embodied learning, which is particularly beneficial for tasks requiring complex visualization or kinesthetic engagement (Wu et al., 2020).

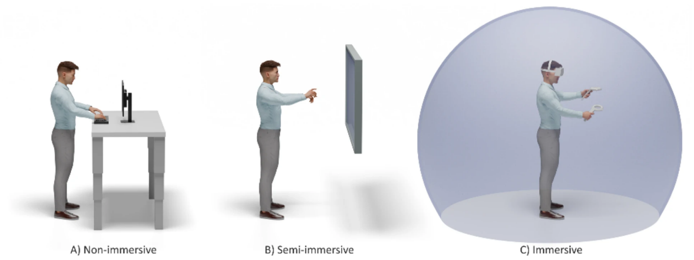

Fig. 1. Non-immersive, semi-immersive and immersive modality (Stracke et al., 2025).

However, the transition toward higher levels of immersion is constrained by financial and infrastructural limitations. High-end HMDs (e.g., Valve Index, HTC Vive Pro) require powerful computers and represent a substantial investment for many institutions.

Unlike conventional virtual platforms or 2D multiplayer online games, IVR systems employ advanced technological components to create a deeply engaging experience. These systems integrate high-precision motion tracking sensors and robust graphics processing units to generate uninterrupted stereoscopic visuals displayed through HMDs (Won et al., 2023). This technical configuration enables real-time synchronization between user movements and virtual environment responses, producing a heightened sense of spatial presence unattainable through traditional screen-based interfaces.

In contrast, open-source platforms such as OpenSimulator offer a cost-efficient entry point into immersive learning. When combined with affordable consumer devices such as the Meta Quest 2, institutions can achieve an effective transition from non-immersive or semi-immersive environments to fully immersive VR while minimizing costs and maintaining pedagogical quality.

1.2 Immersive vision and technological transition

The VR market offers diverse HMDs catering to different needs and budgets. Standalone headsets like the Meta Quest 3 (Meta, 2025) provide wireless freedom with integrated processors, while PC-tethered systems such as the Valve Index (Valve Corporation, 2019) deliver high-fidelity graphics for advanced users. Enterprise-focused devices (Varjo XR-4 series) offer industrial-grade precision for professional applications (Varjo, 2023). Recent advancements in mixed reality (Apple Vision Pro) blur boundaries between physical and digital environments (Apple Inc., 2024). Cost-effective options like PICO 4 (PICO Interactive, 2022) compete in the consumer segment, though performance varies significantly across price tiers.

The transition from conventional 2D/3D interfaces to fully immersive experiences with open-source software presents distinct technological and perceptual challenges. The goal is achieving what researchers' term 'unconscious presence', a state where users become so thoroughly immersed that they cease to perceive the virtual environment as artificial (Gonçalves et al, 2021). This phenomenon represents the gold standard for VR systems, yet its attainment requires careful attention to multiple interdependent factors.

Three critical components emerge from the literature as fundamental to this transition. First, high-quality visual representation forms the foundation of immersion, requiring exceptional graphic fidelity, realistic textures, and precise spatial rendering to create convincing virtual spaces (Chessa et al., 2016; Mastrolembo Ventura et al., 2022). Second, accurate positional and motion tracking proves essential, as even minor latency or inaccuracies in head and body tracking can disrupt the illusion of presence and potentially induce simulator sickness (LaViola, 2000). Third, spatially rendered 3D audio significantly enhances immersion when properly synchronized with visual events, with studies demonstrating its role in reinforcing spatial awareness and emotional engagement (Cabero Almenara and Puentes Puente, 2023; Sosa Jiménez et al., 2020).

To systematically examine these requirements, we conducted a comprehensive review of IVR literature, incorporating foundational studies and recent technological advancements (Chessa et al., 2016; Dong and Lee, 2022). This synthesis reveals that achieving unconscious presence depends not merely on individual system components performing optimally, but on their seamless integration and synchronization within the virtual environment.

Overall, immersive vision represents a critical stage in the evolution of digital learning environments. By examining the technical foundations of immersion and aligning them with learner characteristics and institutional constraints this revised section prepares the rationale for the open-source implementation detailed in the methodology.

1.3 Immersive virtual reality for education

As an implementation of VR technology, OpenSimulator emerges as a free 3D virtual world platform specifically designed for educational institutions across all academic levels, from K12 schools to universities. This tool facilitates a paradigm shift in knowledge transfer by integrating VR and immersive technologies to create engaging learning experiences. As Martínez-Gutiérrez et al. (2024) highlight, this tool provides a virtual world where students can freely explore while simultaneously interacting with their teachers, enabling collaborative discovery of new learning horizons. In this context, virtual worlds serve as a complementary, transferable, and effective alternative for enhancing student-instructor interaction and immersive learning experiences.

Open-source platforms such as OpenSimulator provide a viable foundation for educational institutions seeking to deploy IVR without incurring the high costs associated with commercial metaverse solutions. These platforms support customizable virtual campuses, collaborative learning spaces, and multi-user simulations, all while avoiding licensing fees and offering broad interoperability with diverse hardware and software ecosystems.

OpenSimulator distinguishes itself through its modular architecture and high degree of configurability. The platform enables both end-users and developers to configure the software to meet specialized needs, facilitating diverse implementation use cases (Tlili et al., 2022). This versatility makes it especially suitable for applications ranging from pedagogical simulations and vocational training modules to virtual collaboration hubs and interactive entertainment systems (Saenz, 2025).

OpenSimulator's versatile architecture embodies many key characteristics that leading experts associate with metaverse development. Industry leaders have conceptualized the metaverse through complementary perspectives. Zuckerberg (2021) characterizes it as a persistent, 3D digital ecosystem that blends virtual and augmented reality (AR) to enable novel forms of social interaction and shared presence across geographical boundaries. Similarly, Sweeney (2021) of Epic Games describes it as an evolving network of interoperable virtual spaces supported by common technical standards, where users collectively generate and experience digital content across gaming, education, and social domains.

Previous studies demonstrated that IVR environments yield significantly better learning outcomes than traditional instructional methods like lectures or low-immersion media. These comprehensive studies indicate a moderate effect size advantage for IVR across various educational contexts, suggesting its potential as a transformative pedagogical tool (Hamilton et al., 2021; Wu et al., 2020). The increased sensory engagement and spatial presence afforded by IVR systems appear to facilitate knowledge retention and conceptual understanding more effectively than conventional two-dimensional learning formats.

Despite these advantages, institutions must consider several challenges before integrating IVR into educational programs. Performance bottlenecks, hardware limitations, and connectivity issues can affect the quality of immersive experiences.

Finally, the transition toward IVR is influenced by cost considerations related to hardware acquisition. Devices such as Meta Quest 2 provide an affordable entry point, with publicly documented pricing available from Meta's official platform (Meta Support, 2025). In contrast, enterprise-oriented HMDs like the Varjo XR-4 exceed USD 3,000 and require high-end workstation hardware.

1.4 Study objectives

This study aims to develop and document a reproducible implementation framework for adapting open-source 3D virtual worlds (OpenSimulator) to IVR in the educational field, using consumer hardware (Meta Quest 2) and modified open-source viewers (Firestorm VR).The proposed framework addresses both pedagogical and technological needs, ensuring alignment with the characteristics of contemporary learners as well as the financial limitations of higher education institutions.

The research will pursue three key technical objectives to achieve this goal:

- **O1**: To evaluate the cost-saving potential of this open-source approach by comparing total expenses (hardware and software) against commercial VR education solutions
- **O2**: To identify and optimize technical bottlenecks in the implementation process (e.g., latency, visual rendering settings, wireless streaming) that affect educational usability.
- **O3**: To establish best practices for deploying this solution in resource-constrained institutions, including minimal hardware requirements and scalability considerations.

2 Methodology

This study employed a mixed-methods research design combining quantitative hardware benchmarking with qualitative usability analysis to evaluate the feasibility of implementing an open-source immersive virtual reality (IVR) ecosystem, focusing on three core components: (1) OpenSimulator as the virtual world platform, (2) Firestorm VR as the optimized viewer, and (3) Meta Quest 2 as the target HMD. Performance metrics - including frames per second (FPS) and latency - were systematically recorded across all hardware configurations.

As an open-source alternative to Second Life, OpenSimulator provides a robust framework for developing and managing 3D virtual environments. The platform offers comprehensive capabilities for building virtual spaces, customizing environmental elements, and facilitating real-time interaction among multiple users within these simulated settings. Its architecture supports the creation of immersive educational environments while maintaining flexibility for technical adaptation and pedagogical integration. OpenSimulator provides 3D visualization through conventional LCD monitors, with user interaction primarily mediated through keyboard-based controls. This study investigates methods to enhance interaction quality in virtual environments through advanced immersion techniques.

The central research question examines: How can we effectively transition users from conventional 2D/3D displays to fully IVR experiences while maximizing the sense of physical presence and natural interaction? This research question focuses on overcoming the technical and perceptual challenges of creating seamless immersion, where users wearing VR headsets (Meta Quest 2 in this study) can achieve authentic spatial awareness and intuitive control. Currently, newer versions of the headset are available, however, for this research, the Meta Quest 2 was used due to current availability, although the methodology is adaptable for future HMD updates. Taking into account hardware benchmarking and the feasibility of implementing a low-cost immersive virtual reality (IVR) ecosystem, a comparative table of IVR-compatible software is shown in Table 1.

Table 1. Comparative analysis of VR/3D world software

Software	License	IVR Compatibility	Suitability for Education
OpenSimulator	Open-source	Via Firestorm VR Mod	Highly flexible and scalable; ideal for low-budget institutions (OpenSimulator, 2024).
Second Life	Free / Commercial	Limited (no native IVR)	Useful for exploration but not optimal for IVR teaching (Linden Lab., 2024).
Mozilla Hubs	Open-source	Partial (WebXR)	Highly accessible; limited graphic fidelity (Mozilla, 2024).
ENGAGE XR	Commercial	Native IVR	Strong for enterprise training; expensive for large classes (Engage XR, 2025).
ClassVR / Eduverse	Commercial	Native IVR	Good plug-and-play solution but costly and proprietary (ClassVR, 2025).
Unity + VR Toolkit	Free tier / Paid	Native IVR	Excellent for custom experiences; requires advanced skills (Unity Technologies, 2024).

A secondary question investigates: What minimal hardware specifications (GPU/ CPU/ RAM) are required to maintain acceptable performance in OpenSimulator-based IVR learning environments? For an optimal and comfortable IVR experience, 90 FPS is widely considered the minimum acceptable standard, with 120 FPS or higher being ideal to minimize latency, motion sickness, and disorientation (Cobb et al., 2019).

Below 90 FPS, users may experience cybersickness, lag, and reduced presence (Rebenitsch & Owen, 2016). Although FPS is largely limited by video processing capabilities, a comparison of VR headsets to analyze the display FOV and some of their pros and cons can be viewed in Table 2.

Table 2. Comparative analysis of representative VR headsets

Device	Display / FOV	Cost	Pros	Cons
Meta Quest 2	1832×1920 per eye ∼100°	USD $249 (Meta, 2025)	Affordable, wireless, easy to deploy.	Requires PC link for high-end IVR.
Valve Index	1440×1600 per eye 130°	USD $999 (Valve Corporation, 2019)	Excellent fidelity, wide FOV.	High cost; requires powerful PC.
HTC Vive Pro 2	2448×2448 per eye	USD $799 (HTC Corporation, 2024)	Extremely high resolution.	Expensive; complex setup.
PICO 4	2160×2160 per eye	USD $429 (PICO Interactive, 2022)	Good balance price/quality.	Limited availability in some regions.
Varjo XR-4	2880×2720 per eye	USD $3,990 (Varjo, 2023)	Best-in-class fidelity.	Prohibitively expensive for most institutions.

This inquiry, along with parallel investigations into cost-effective adaptation methods, directly supported the development of an implementation framework for converting open-source 3D virtual worlds to IVR educational environments.

2.1 OpenSimulator configuration

As an open-source alternative to Second Life, OpenSimulator was selected due to its cost-effectiveness, modular architecture, and extensive configurability for multi-user educational environments. Although is natively designed for Windows systems, this implementation was deployed on a Linux Debian 12 platform (kernel 5.10.0-33) to leverage its superior memory management capabilities. The adaptation process necessitated the Mono Project's compatibility layer to bridge the Windows-native OpenSimulator with the Linux environment, ensuring stable operation while optimizing resource allocation.

Mono is an open-source implementation of the .NET framework, designed to allow developers to create applications across platforms. In this study, Mono was installed via Debian's official repositories, as shown in Fig. 2.

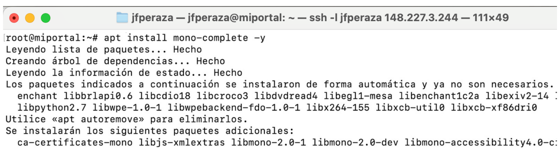

Fig. 2. Mono's project installation.

Version 6.8 of the Mono project was used, with SUID permissions enabled for execution via bash shell from the command line, as shown in Fig. 3.

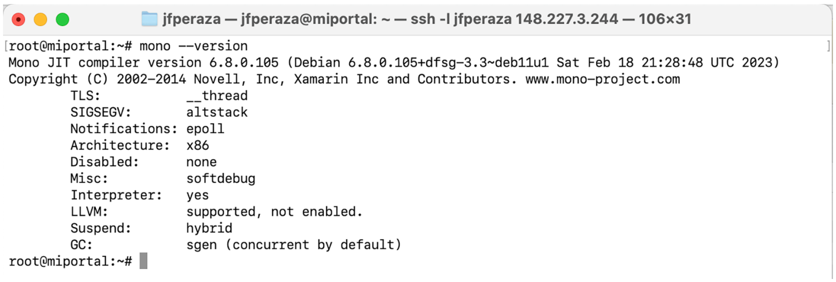

Fig. 3. Mono command line version and execution.

Once the installation process of the Mono Project was completed, a documentary review was conducted to determine which database management system would best meet the requirements of this implementation. Both PostgreSQL and MySQL were evaluated, considering factors such as stability, resource optimization, and availability of documentation.

Although PostgreSQL exhibited superior performance in benchmarked parameters, MariaDB (an open-source MySQL derivative) was selected due to its more efficient memory management, comprehensive documentation, and robust community support (Zapata, 2024). While marginally less performant, these practical advantages aligned better with project requirements. Fig. 4 illustrates the database creation process in MariaDB.

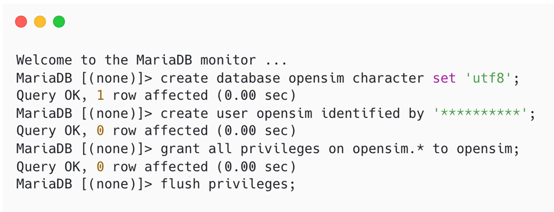

Fig. 4. Database creation in MariaDB.

The OpenSimulator platform was installed according to the following procedure: First, a directory was created within the home folder of a non-administrative user account. The latest stable release (v4.2) was obtained from the official GitHub repository. After extracting the compressed files, the source code directory was accessed, and the compilation process was executed using default build parameters (Olivarría González et al., 2023). This installation approach was adopted to preserve system security while guaranteeing compatibility with the experimental environment. The compilation process is illustrated in Fig 5.

Fig. 5. Compiling OpenSimulator.

After the installation process, the initial virtual world configuration was implemented through modification of the ‘MyWorld.ini’ configuration file. This critical setup phase established the foundational parameters for the virtual environment. The configuration procedure and resulting parameters are documented in Fig. 6, which presents the complete set of implemented settings and their organizational structure.

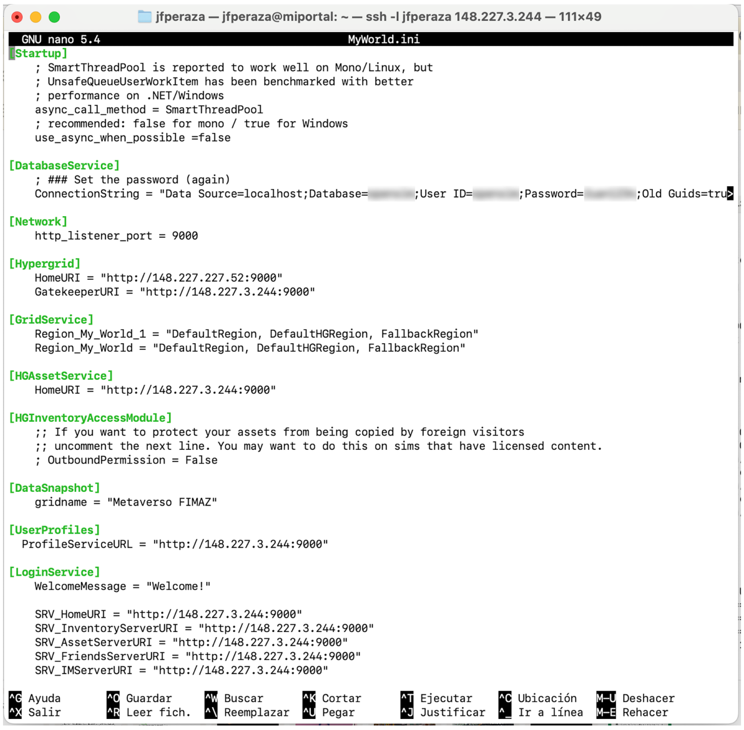

Fig. 6. First virtual world setup.

The virtual world deployment began with initialization of the core OpenSimulator system. A background session was established using the GNU screen terminal multiplexer, followed by execution of the metaverse environment through specific command-line instructions. The complete command sequence and system response were documented in Fig. 7, showing the startup protocol.

```
opensim@gnu:~$ screen -S opensim
opensim@gnu:~$ mono OpenSim.exe
```

Fig. 7. Command sequence to start OpenSimulator.

Finally, OpenSimulator environment was accessed through a web browser by entering the server's IP address and the port configured in the MyWorld.ini file. For web-based administration, the system utilized port 9000, forming the access URL: http://serverIP:9000/wifi/. Fig. 8 illustrates the browser interface used for metaverse configuration, displaying the administrative dashboard and connectivity settings.

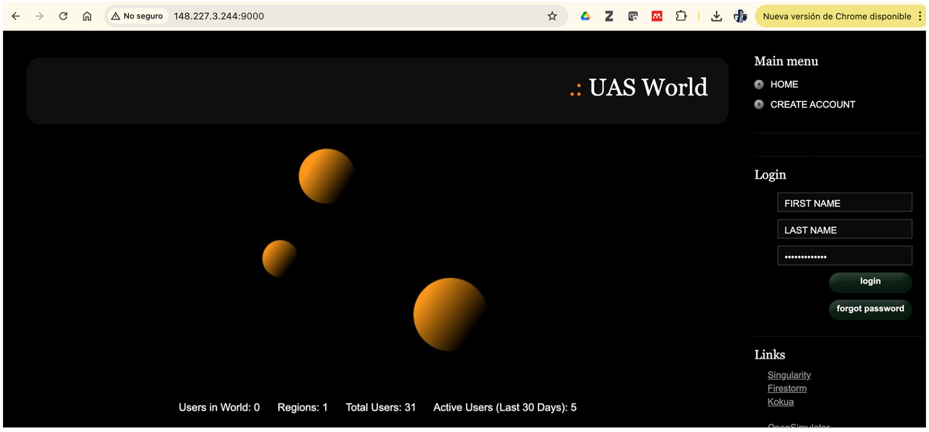

Fig. 8. Metaverse web administration interface.

Following the metaverse configuration and user account creation, the connection was established from a client PC using Firestorm Viewer (v6.6.9), a widely adopted open-source client for virtual world access. The compatible version was downloaded according to the client's operating system specifications (Windows 11 or Ubuntu 22.04 LTS). As noted by Lyon (2024), Firestorm serves as the gateway to virtual environments, analogous to web browsers for Internet access. Fig. 9 documents the authentication interface displayed during login to the virtual world created 'UAS World' using the test account 'Juan Peraza'.

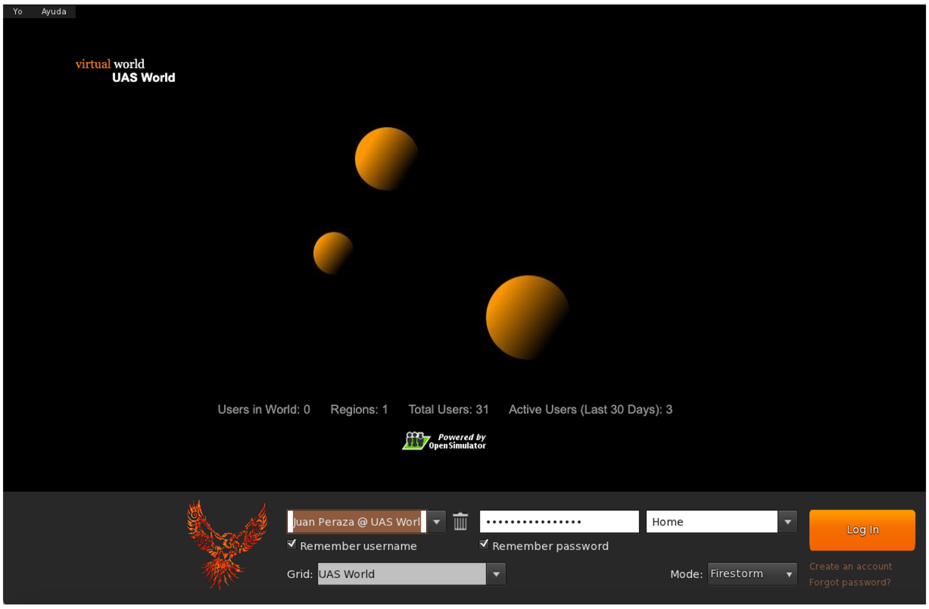

Fig. 9. Firestorm login interface.

After successful login through the Firestorm viewer, the access to the UAS World virtual environment was established. Fig. 10 presents the customized avatar within the metaverse, displaying the preconfigured clothing options and modified physical characteristics that were implemented for user representation.

Fig. 10. Customized avatar appearance in UAS World virtual environment.

2.2 Immersive VR Integration

After establishing OpenSimulator's operational status, the system configuration proceeded with the integration of immersive visualization components. The Meta Quest 2 headset was connected through Virtual Desktop software to enable VR functionality. This hardware-software combination facilitated the transformation of the virtual environment into a fully immersive experience.

2.2.1 Meta Quest 2. The study selected pre-existing Meta Quest 2 headsets as the immersive interface. The devices' ergonomic design, high-resolution display, and submillimeter motion tracking precision (Fig. 11) were identified as critical features for sustained educational use. Unlike previous models, this standalone headset required no external PC connection, offering enhanced portability and accessibility (Meta, 2025). These technical characteristics made it particularly suitable for immersive virtual environment applications.

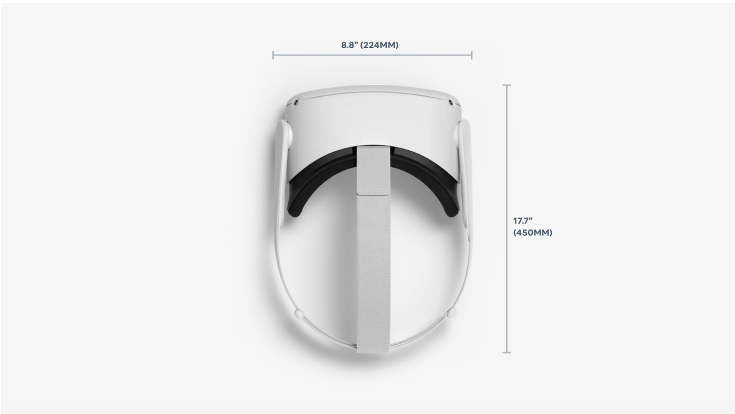

Fig. 11. Meta Quest version 2 (Meta, 2025).

The Meta Quest 2 employed an integrated camera-based tracking system to monitor head and hand movements, facilitating natural interaction within virtual environments. As a standalone device requiring no external computer tethering, it offered enhanced portability while maintaining stable performance. These technical capabilities, combined with access to an extensive application ecosystem (Meta, 2025), positioned the headset as an optimal solution for diverse VR applications, including gaming, social interaction, and immersive educational experiences.

2.2.2 Virtual desktop.

The virtual desktop implementation utilized a cloud-based desktop virtualization service, which was achieved through software emulation on remote virtual devices. This solution was specifically designed for teleworking applications, enabling remote network access to documents and computing resources. Prior to deploying the virtual desktop infrastructure, an assessment of user requirements was conducted, and the network infrastructure was prepared. The implemented system supported wireless connectivity to multiple computers, facilitating various applications including media viewing, Internet browsing, gaming on virtual displays, and PC VR game streaming. The virtual desktop application was selected for its optimized performance characteristics, featuring low-latency operation and high-quality streaming capabilities (Canorea, 2025).

2.2.3 Connecting Meta Quest 2 to the computer.

The connection between devices was established using either a USB-C data cable or wireless transmission. Both methods were implemented, though wireless connectivity was prioritized to eliminate potential safety hazards and mobility restrictions associated with physical cabling. Following installation of required applications, network configuration was performed via a local area network (LAN), ensuring all devices operated on the same network. The Meta Quest 2 headset was specifically connected to a Wi-Fi 6 network, achieving transmission speeds up to 9.6 Gbps. This high-speed connection enhanced FPS rates and improved visual rendering quality during operation.

2.2.4 SteamVR and Firestorm VR setup.

The VR implementation began with SteamVR, described by its developers as a comprehensive platform for VR content across multiple hardware systems, including Valve Index, HTC Vive, Oculus Rift, and Windows Mixed Reality headsets (Valve Corporation, 2025). Following installation on a Windows 11 system, the specialized Firestorm VR (version 6.6.8 + VR Mod 6.3.3) was configured. This modified viewer, adapted for Second Life and OpenSimulator compatibility with HMDs, employed SteamVR for system integration.

The VR implementation followed a minimalistic design philosophy to reduce maintenance requirements and enhance long-term viability. Successful operation required installation of both Meta Quest 2 and SteamVR drivers. Upon launch, Firestorm VR automatically initialized all necessary SteamVR subsystems for headset functionality.

The VR capabilities described are based on a dual-screen split of the primary display, which is essential for VR headset compatibility. One screen is rendered per eye, helping to create the immersive experience, as shown in Fig. 12. This feature is not supported by the standard Firestorm client, hence the necessity of the VR version.

Fig. 12. View from inside Firestorm VR (Austin, 2022).

2.2.5 Firestorm VR and Meta Quest 2 configuration parameters.

Following device connection, multiple visual parameters required configuration within the Firestorm VR interface to optimize display performance through the Meta Quest 2 headset. Initial setup configurations frequently exhibited technical challenges including improper distance scaling, focus inaccuracies, and incorrect lens separation parameters. These issues were systematically addressed through iterative calibration of the VR rendering settings. Key parameters to configure include:

- Interpupillary Distance (IPD): This refers to the distance, in millimeters, between the user's pupils. For optimal image clarity, the lens spacing should closely match the user's IPD. Meta Quest 2 headsets are best suited for IPD values ranging from 56 mm to 70 mm, which corresponds to approximately 95% of the adult population (Meta, 2025).
- Focus distance: This setting adjusts the focal distance for image clarity.
- Texture shift and texture zoom: These parameters enhance image texture quality.
- Field of View (FOV): In extended reality (XR), FOV refers to the extent of the virtual or augmented environment visible through the headset at a given moment.

The FOV was identified as a critical parameter influencing UX in immersive environments. In the VR implementation, the expanded FOV enhanced spatial awareness and immersion through increased peripheral content visibility (Fig. 13). By contrast, the AR system operated with a narrower FOV, which constrained the superimposition area for digital elements onto physical environments. These specifications aligned with established guidelines from the Interaction Design Foundation (2023), with the VR configuration specifically optimized to maintain the recommended 90°-110°range for optimal performance.

Fig. 13. Ideal FOV area in VR (Interaction Design Foundation, 2023).

When designing immersive experiences, you'll find VR and AR require fundamentally different approaches to FOV optimization. In VR, you should target a wide 90°-110° FOV to maximize presence but must carefully balance this with comfort considerations, avoiding extreme peripheral motion that could trigger simulator sickness. The expanded viewport lets you create enveloping environments, though rapid movements near the edges may disorient users. Conversely, AR's narrower 30°-50° FOV forces you to work within tighter constraints (Interaction Design Foundation, 2023). Here, you need to anchor key content centrally (Fig. 14) and maintain clear visibility of all interactive elements, as users can't rely on peripheral awareness like in VR. While VR allows you to construct entire worlds, AR demands you strategically layer digital elements onto physical spaces without requiring excessive head movement.

Both mediums share the need for thoughtful content placement, but where VR pushes you to expand the view, AR challenges you to make every degree count through precise spatial composition and context-aware design.

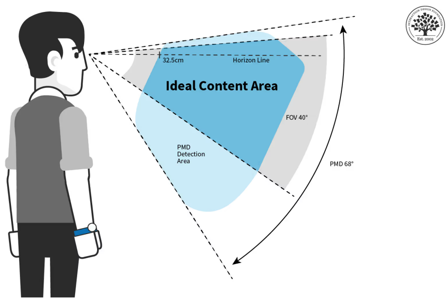

Fig. 14. FOV restricted in AR (Interaction Design Foundation, 2023).

Based on the established technical parameters, the Meta Quest 2 headset was configured with the following optimized settings, as documented in Fig. 15: IPD of 68 mm, focus distance set to 10 units, texture shift adjusted to 18.5%, texture zoom at 79%, and FOV fixed at 100°. These calibrated values represented the optimal balance between visual comfort and immersive quality for the experimental conditions.

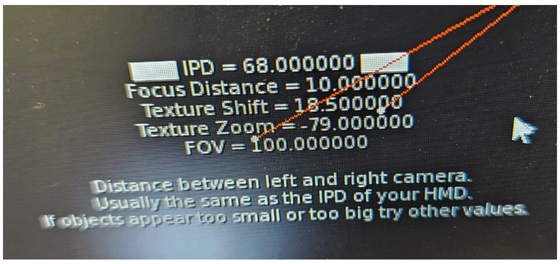

Fig. 15. Firestorm VR configuration.

The final configuration was specifically calibrated for an adult test subject (age 42 years), verifying that the configured IPD falls within the normal range for adults (Meta, 2025). This age-specific calibration ensured optimal visual alignment and comfort during extended use sessions.

Continuing with the immersive vision conversion process, and after successfully setting up OpenSimulator, Firestorm VR, and configuring the Meta Quest 2 headset, the next step involves establishing the connection between SteamVR and Firestorm

VR. It is worth recalling that Firestorm VR is a customized viewer derived from the Firestorm client, while SteamVR is a VR module developed by Steam, both installed on a PC running Windows 11.

To establish connectivity between Firestorm VR and SteamVR, the following procedure must be executed: First, launch Firestorm VR on the Windows 11 system. Then, press CTRL+TAB to activate or deactivate the SteamVR driver. This operation is required every time the user initiates VR mode following system startup.

2.3 Basic avatar usage within the metaverse with immersive vision enabled

Traditional avatar navigation in the virtual environment presented significant complexity, requiring keyboard inputs for movement and mouse control for view orientation. The implementation of immersive vision technology substantially improved this interaction paradigm by introducing natural head-tracking capabilities, thereby eliminating dependence on manual view direction adjustment. Furthermore, the system was enhanced through integration of an Xbox game controller connected via Bluetooth, as documented in Fig. 16. This peripheral device provided more intuitive avatar movement control compared to standard keyboard input methods.

Fig. 16. Xbox control (Microsoft, 2025).

3 Results

The transition from conventional open-source 3D virtual world into an immersive experience was successfully implemented through the installation and configuration of specialized tools. The core components included: OpenSimulator as the virtual world platform, Firestorm VR as the optimized viewer for VR environments, and SteamVR as the compatibility module for immersive device integration, specifically adapted for the Meta Quest 2 headset. This integrated system enabled full transformation of conventional 3D content into immersive educational experiences while maintaining open-source accessibility.

3.1 Hardware configuration

The results of the hardware benchmarking, immersive configuration, and cost analysis support the feasibility of this approach for resource-limited higher education institutions. Regarding the headsets, Table 3 compares standalone, PC-tethered, and enterprise VR headsets based on representative models, principal uses, and price ranges with data sourced from manufacturer specifications. It is important to note that the prices shown in this section were obtained directly from the provider's website, Amazon México or Amazon US.

Table 3. Key features of major VR headset categories (Meta, 2025; Valve Corporation, 2019; Varjo, 2023)

Type	Example	Best For	Price Range	Source
Standalone	Meta Quest 2/3	Consumers / Education	USD $300–$500	Amazon MX
PC-Tethered	Valve Index	Enthusiasts / Developers	USD $600–$1,000	Provider's Web
Enterprise	Varjo XR-4	Professional Training	USD $3,000+	Provider's Web

The study prioritized server-side hardware specifications for hosting the core OpenSimulator metaverse processes, distinguishing them from client-side requirements for Firestorm VR operation. Notably, client machines demanded superior hardware capacity due to local image rendering responsibilities, necessitating robust performance for optimal visual fluidity.

Initial tests with Intel i3 and i5 server processors yielded suboptimal frame rates ($\leq$ 20 FPS). Subsequent implementation of an Intel i7 processor demonstrated significant improvement, achieving peak performance of 237 FPS. Table 4 details the optimized production server specifications deployed in the final implementation.

Table 4. Minimum optimal hardware requirements for OpenSimulator server operation

Hardware	Description
CPU Processor	Intel(R) Core(TM) i7-8700 CPU @ 3.20 GHz
Graphics Card	Integrated
GPU	Coffee Lake GT2, 192 cores
RAM Memory	8 GB
Hard Drive	512 GB SSD

Client-side hardware requirements were more demanding due to the client-dependent rendering architecture, which shifted most graphical processing from the server to local machines. The project evaluated three hardware configurations: An initial test system with an Intel i5 processor (8GB RAM) and GTX 1660 Super GPU (6GB VRAM, 1408 CUDA cores) exhibited critical performance limitations, failing to maintain stable connectivity between SteamVR and Firestorm VR.

Subsequent testing with an equivalent Intel i7 configuration replicated these interoperability issues. Ultimately, a high-performance workstation with a 14th-generation Intel i9 processor (16 cores, no integrated graphics) and dedicated Gigabyte PCI-Express GPU resolved the bottlenecks. Complete specifications are detailed in Table 5.

Table 5. Client-side hardware configurations evaluated

Component	Config A	Config B	Config C
CPU Processor	Intel Core i5-6500 4 cores, 3.6 GHz	Intel Core i7-7700 4 cores, 5.1 GHz	Intel Core i9-12900F 16 cores, 5.1 GHz
Graphics Card	NVIDIA GTX 1660 Super 6 GB VRAM, PCIe 4.0	NVIDIA GTX 1660 Super 6 GB VRAM, PCIe 4.0	Gigabyte Radeon RX 6600 8 GB GDDR6, PCIe 4.0
GPU Cores	1408 stream processors	1408 stream processors	1792 stream processors
System Memory	8 GB DDR3 RAM	8 GB DDR3 RAM	32 GB DDR4 RAM
Storage	512 GB SSD	512 GB SSD	1 TB NVMe SSD

3.2 Inmersive Rendering and Quality

The 237 FPS shown in Fig. 17 (client-side Firestorm testing) were achieved using the "Config C" hardware configuration for client, as previously specified.

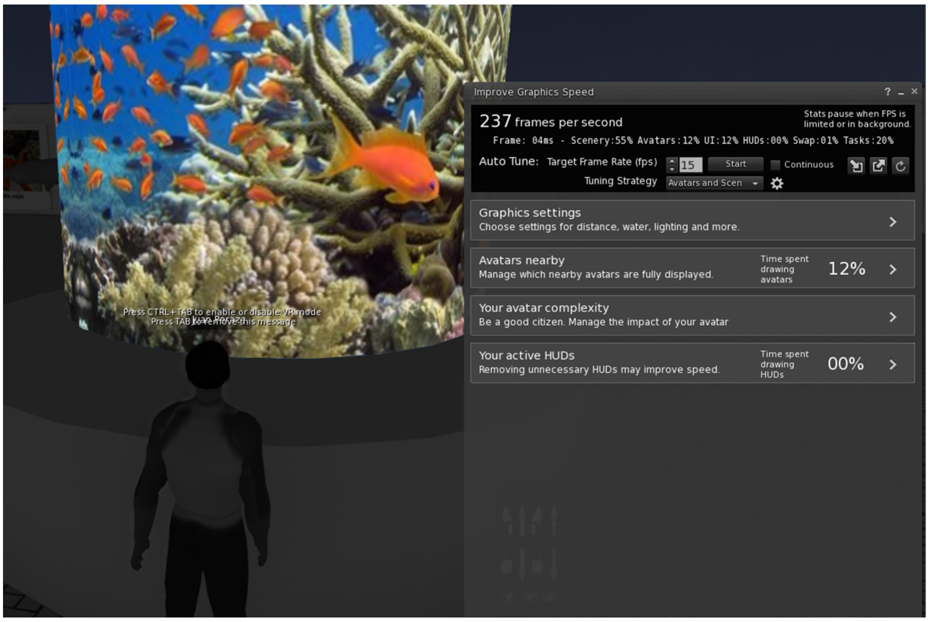

Fig. 17. FPS results before implementing immersive vision.

The implementation process involved three key technical adaptations: graphics parameter optimization, IPD calibration, and FOV adjustment. These modifications enabled seamless integration into the platform and fluid visual performance. System latency was maintained at optimal levels thanks to Wi-Fi 6 network connectivity between the headset and the host computer, enabling seamless interaction with the environment in real time.

Fig. 18 shows the performance results comparing two configurations, SteamVR with Firestorm VR achieved 90 FPS on the Meta Quest 2, versus 237 FPS in Firestorm's non-immersive mode.

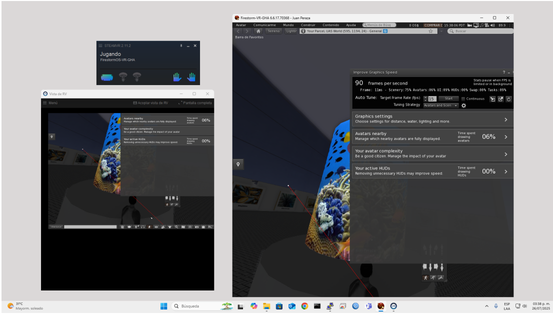

Fig. 18. FPS results before implementing immersive vision.

The resulting configuration demonstrated full functionality for immersive OpenSimulator visualization, with head-tracking responsiveness that met all performance benchmarks. Stability testing confirmed consistent performance during extended sessions ($\geq$ 2 hours continuous use), with no significant frame rate drops or system crashes. These results validate the technical feasibility of transforming conventional open-source 3D environments into immersive experiences, establishing a foundation for educational applications requiring interactive learning frameworks.

3.3 Cost Analysis and Price Sources

As institutions seek to modernize pedagogical approaches and prepare for the digital future of education, evaluating the financial feasibility and scalability of VR implementations becomes imperative. Table 6 describes a cost analysis of commercial and open-source IVR platforms tailored for educational purposes. The commercial IVR platforms examined offer turnkey or subscription-based solutions that include pre-packaged content, technical support, and varying degrees of customization. In contrast, open-source alternatives such as OpenSimulator paired with Meta Quest 2 present a highly adaptable and cost-effective model but in addition to HMDs, it requires a PC and greater technical skills for configuration and maintenance.

It should be noted that some platforms, including Class VR and ENGAGE XR, impose minimum purchase requirements for either licenses or hardware equipment, which may affect their accessibility. Unlike custom solutions, commercial platforms prioritize plug-and-play usability and low technical knowledge requirements. However, their cumulative costs can become significant over time, particularly when scaling to larger classrooms or entire campuses. In contrast, open-source solutions, notably those based on OpenSimulator paired with Meta Quest 2 (or similar headsets), offer a low-cost, high-flexibility alternative. The software itself is free to download and deploy, with the primary investment being hardware and the technical expertise required for configuration and maintenance of the virtual environment.

Table 6. Commercial vs. Open-Source IVR solutions for education

Platform	Estimated Minimum Hardware Cost	Educational License/ Subscription	Estimated Minimum Annual Cost
ClassVR (Stemfinity, 2025)	˜USD $4,900 (8 units)	Eduverse Portal license: USD $769/year	˜USD $5,700 (hardware + license)
Wonda VR (Wonda VR, 2024)	˜USD $300 per headset	Free trial; Basic plan: USD $350/month	˜USD $4,500 (hardware + license)
ENGAGE XR (ENGAGE XR, 2025)	˜USD $300 per headset	EDU License: USD $190/user/year	˜USD $1,250 (hardware + license)
Bodyswaps (Bodyswaps, 2025)	˜USD $300 per headset	Free trial; EDU license: USD $80/user/year (100–250 users)	˜USD $380 (hardware + license)
Open-Source (OpenSimulator, 2024)	˜USD $700 per station	Free (open-source software)	˜USD $700 (hardware)

Table 7 presents a comparative analysis between the average cost of commercial Immersive Virtual Reality (IVR) solutions and a free, open-source ecosystem based on OpenSimulator. The results indicate that the adoption of open-source IVR reduces the initial investment by approximately 60–70% in contrast to commercial alternatives. This cost differential demonstrates that open-source IVR environments constitute a financially viable pathway for institutions with limited budgets, significantly enhancing the accessibility and scalability of immersive learning implementations.

Table 7. Cost Analysis and Price Sources

Solutions	Hardware Cost	Software License Cost	Sources
Commercial IVR Solutions	USD $4,900 to $7,000	˜USD $300 to $1,200	ClassVR (2025) ENGAGE XR (2025) Bodyswaps (2025)
Open-Source IVR Solution	USD $1,400 to $1,700	Free	OpenSimulator Firestorm VR SteamVR

4 Discussion

The results of this study provide compelling evidence that open-source immersive virtual reality (IVR) environments can serve as effective and affordable platforms for enhancing student engagement and learning outcomes in higher education. The key findings performance benchmarking, cost analysis, and comparative software/hardware evaluation must be interpreted in relation to both, the pedagogical issues introduced earlier and the technological constraints facing institutions.

Students tend to exhibit reduced attention spans, require high interactivity, and respond positively to multisensory stimuli. The stable head-tracking, high frame rates, and improved embodiment achieved in the final hardware configuration (Intel i9 + Radeon RX 6600 + Meta Quest 2) directly contribute to sustaining attention and reducing cognitive fatigue, critical factors for today's learners and in the technological field this configuration demonstrated a clear performance hierarchy maintaning a stable SteamVR-Firestorm VR integration. This aligns with prior research by (Radianti et al. 2020) indicating that client-side rendering in virtual environments demands robust single-threaded CPU performance (evidenced by the i9's 5.1GHz boost) and dedicated GPU resources (1792 stream processors). Recurrent bottlenecks in i5/i7 configurations with identical GPUs demonstrate that performance in OpenSimulator-based IVR environments is constrained not only by graphical capacity but also by CPU processing capabilities.

The performance analysis also showed that underpowered systems (Configurations A and B) produced low frame rates, high latency, and visual instability. These findings align with the literature indicating that suboptimal VR performance can result in increased cognitive load, reduced presence, and higher susceptibility to cybersickness (Cobb et al., 2019).

The cost analysis demonstrates that open-source IVR ecosystems present a financially viable alternative to commercial solutions. However, cost savings do not come without trade-offs. Open-source implementations require more technical expertise to configure and maintain compared to commercial ecosystems. Institutions must therefore evaluate the balance between affordability and the internal technical capacity needed for long-term sustainability.

While the optimal i9/RX 6600 setup incurred higher initial costs, its 237 FPS output justified the investment for educational deployments requiring prolonged use. This finding contradicts common assumptions that GPU selection alone determines VR performance, as shown when identical GTX 1660 Super GPUs underperformed across different CPU tiers. The 32GB RAM and NVMe SSD likely contributed to texture streaming efficiency (Pellas et al., 2021).

For institutions adopting open-source VR solutions, these results advocate prioritizing: (1) latest-generation CPUs with high clock speeds (> 5GHz) over core count alone, (2) mid-range GPUs with at least 8GB VRAM, and (3) fast storage to mitigate asset loading delays.

5 Conclusion

This study demonstrates the technical and pedagogical feasibility of implementing a cost-effective immersive virtual reality (IVR) ecosystem for higher education using open-source software and affordable consumer hardware. By integrating OpenSimulator, Firestorm VR, SteamVR, and the Meta Quest 2, the research provides a viable pathway for institutions with limited financial resources to transition from traditional 2D/3D interfaces to fully immersive learning environments. From a pedagogical perspective, the study confirms that IVR environments enhance engagement, embodiment, and spatial understanding, consistent with prior empirical evidence (Hamilton et al., 2021; Makransky and Lilleholt, 2018).

The implementation of this open-source ecosystem demonstrated the technical feasibility of cost-effective immersive education systems. Performance benchmarking revealed that client-side hardware specifications, particularly high-clock-speed CPUs ($\geq$ 5.1GHz) and dedicated mid-range GPUs ($\geq$ 8GB VRAM), were critical determinants of system stability, with the Intel i9/RX 6600 configuration achieving optimal frame rates (90 FPS) for educational applications. These findings provide concrete hardware guidelines for institutions seeking to adopt VR while minimizing infrastructure costs.

From a technical perspective, integrating the platforms, along with precise configuration of parameters such as IPD, FOV, and other graphical settings, allowed the environment to be tailored to the user's physiological and perceptual characteristics. This technical refinement ensured a fluid and comfortable experience, minimizing the risks of eye strain, disorientation, or cybersickness, issues commonly reported in poorly configured VR environments. Furthermore, the choice of a wireless connection between the Meta Quest 2 headset and the computer contributed to increased user mobility and comfort, reducing physical barriers to prolonged interaction.

The use of natural-head-movement-controlled avatars and Bluetooth devices such as the Xbox Controller was realized in order to provide the user with a more natural and realistic impression. This configuration facilitated a more natural involvement of students with educational tasks, without the extra cognitive load of using physical keyboards or touch screens. Accessibility of the technology and customization to fit individuals' needs were thus important to achieve the full educational potential of the experience in this respect.

This research indicates that while commercial IVR setups deliver optimal performance, their high cost makes them impractical for budget-constrained institutions. In contrast, the proposed OpenSimulator-based solution with Meta Quest 2, cuts initial costs by approximately 60-70% compared to professional alternatives, without significantly compromising immersive quality. However, this cost reduction requires investment in technical staff for setup and maintenance, which must be factored into cost-benefit analyses. This cost-effectiveness positions open-source VR environments as a sustainable solution for higher education, particularly where scalability and accessibility are priorities.

Overall, the research provides a replicable and scalable model for higher education institutions seeking to adopt immersive technologies in a financially responsible manner. While technical barriers and infrastructure requirements remain, open-source IVR ecosystems represent a promising pathway for democratizing access to immersive learning.

The comparative hardware analysis revealed that clock speeds of both the CPU and GPU significantly impacted OpenSimulator's performance. This work establishes a replicable framework for deploying open-source VR education platforms, balancing performance and affordability. Future research directions should investigate: (1) cloud-rendering alternatives to further reduce client hardware demands, (2) scalability in multi-user learning scenarios ($>$ 20concurrent avatars), (3) adaptive content optimization techniques for heterogeneous student devices, and (4) longitudinal academic outcomes and multidisciplinary implementations to fully realize this technology's transformative potential in education.

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Received September 30, 2025 , revised December 11, 2025, accepted January 12, 2026