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VR-Integrated IoT Twin Laboratory for Real-Time Remote Actuation

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Abstract: This paper presents the concept and early-stage implementation of a Physical Twin Laboratory (PTL) that integrates a Unity-based virtual reality (VR) interface with low-cost IoT hardware to enable simple, real-time remote actuation and feedback. The current prototype demonstrates how a user in a VR environment can control a physical WS2812B LED strip connected to an ESP32 microcontroller over Wi-Fi, establishing a functional VR-to-physical interaction pipeline. Initial tests confirm stable operation and low latency under local network conditions, highlighting the practical feasibility of linking virtual actions with physical devices. While the present setup is intentionally simple, the PTL architecture is designed for future scalability to multi-node IoT networks, more complex sensors and actuators, and higher-fidelity VR interactions. By outlining how additional modules such as lightweight edge-AI for local anomaly detection could enhance safety in larger deployments, this work serves as an accessible foundation for researchers and educators interested in building immersive remote laboratories that replicate real-world lab spaces in a virtual environment. The approach aims to lower barriers for distributed hands-on learning, collaborative experimentation, and scalable remote infrastructure in education and research.

The Physical Twin Laboratory concept is designed to evolve into a flexible framework that can support more sophisticated remote experiments, including real-time data acquisition, simple actuator control, and environmental monitoring using commodity sensors. Future iterations will focus on adding plug-and-play modules so that multiple hardware setups can be linked and synchronized with a shared VR environment, allowing students or researchers to co-experience and co-manipulate physical devices from different locations. The architecture also considers open-source development to encourage adaptation and contribution from the wider research community. By lowering the barrier to building affordable VR-linked IoT testbeds, this work has the potential to expand remote skill training, prototyping, and collaborative learning in engineering education.

I. INTRODUCTION

Recent advances in virtual reality (VR) [1], digital twin technologies [4], and IoT edge computing [6][7] are transforming how engineering education and remote laboratories can be deployed at scale. However, many traditional remote labs [2] still rely on static screen interfaces and limited real-time interaction, limiting their effectiveness in replicating authentic lab experiences. The Physical Twin Laboratory (PTL) presented in this paper builds on the proven benefits of immersive VR [3] and low-cost IoT hardware to demonstrate a flexible, cost-effective prototype system that lets users interact with real-world devices through a VR environment. Using an ESP32 microcontroller and WS2812B LEDs as a testbed, the system achieves reliable, low-latency VR-to-IoT control suitable for broader applications, such as distributed labs, collaborative training, or industrial simulations.

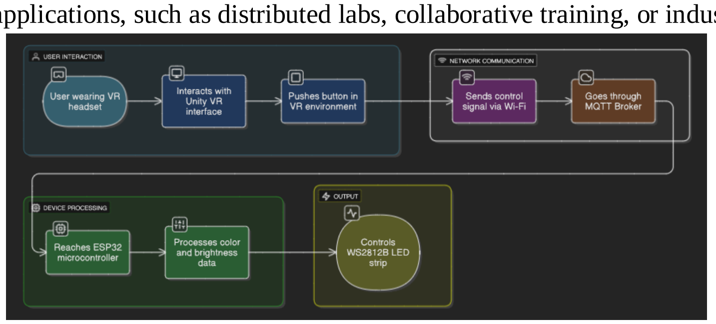

Figure 1: High-Level PTL System Flow Diagram

There is growing evidence that immersive and interactive lab experiences enhance learner engagement, skill retention, and practical understanding [1][3]. Yet the barriers to deploying such solutions at scale remain significant, particularly in resource-constrained environments or institutions lacking high-end infrastructure [2][5].

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By leveraging affordable components and open-source software, the PTL lowers these barriers and provides a foundation for globally distributed, collaborative experimentation. It also opens opportunities for hybrid learning models, where students and instructors can co-exist and operate equipment remotely while experiencing realistic presence.

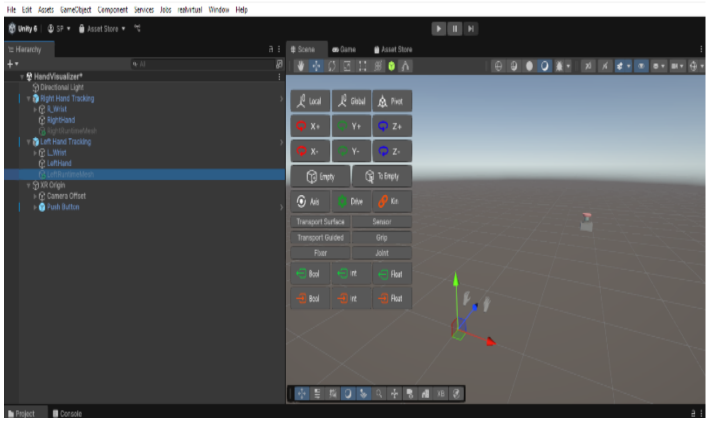

Figure 2: Early VR prototype showing virtual hand pressing a button to control real-world light.

The PTL aims to address the increasing need for accessible, resilient, and scalable learning infrastructures [5]. By combining edge intelligence [6] with modular hardware, the platform supports future extensions to multi-node sensor networks, real-time safety monitoring, secure remote actuation, and multi-user VR learning spaces that bridge physical distance without compromising hands-on experience. Furthermore, it lays the groundwork for integration with advanced digital twin ecosystems [4], where real-time data feeds and virtual replicas enable predictive maintenance, process optimization, and remote troubleshooting. This work demonstrates a foundational step toward immersive, remotely operated labs that could redefine global education, research, and training for the next generation of learners.

II. RELATED WORK

Remote laboratories have evolved significantly over the past two decades, offering students access to physical equipment via online interfaces [2]. Early platforms provided basic remote access but often lacked real-time feedback and practical interactivity. More recent implementations integrate webcams, streaming tools, and basic sensor readouts, but they remain screen-based and do not replicate authentic lab presence or tactile interaction. Research has explored how virtual reality environments can fill this gap by providing a sense of embodiment and spatial context that enhances skill development and engagement [1][3].

Several digital twin frameworks have been developed to synchronize virtual and physical systems for industrial and educational applications [4]. While they demonstrate the feasibility of real-time monitoring and control, most examples focus on large-scale manufacturing or industrial IoT. Few projects adapt these ideas to low-cost, modular educational labs accessible to students worldwide, especially in resource-constrained contexts.

The introduction of IoT-enabled devices and affordable microcontrollers adds new capabilities but also raises concerns about communication latency, security of remote commands, and system scalability [6][7]. Prior cloud-based laboratory models [5] typically depend on proprietary systems, high-cost hardware setups, or restrictive licensing, limiting their adoption in smaller institutions. In contrast, the PTL prototype combines Unity-based VR, commodity microcontrollers, and Wi-Fi networking to offer a practical, affordable, and adaptable solution for institutions with limited budgets.

Emerging trends point toward combining edge computing with remote labs to handle local data processing, reduce round-trip latency, and improve safety by detecting anomalies before they affect physical devices [6]. Other studies have begun to explore collaborative VR laboratories, multi-user sessions, and integration of AI-based assessment modules to personalize student learning. However, these projects often remain isolated pilots without open frameworks for broader replication.

Additionally, there is growing interest in integrating haptic feedback, holographic displays, and mixed-reality elements to further blur the boundaries between physical labs and virtual learning spaces. Such innovations promise deeper immersion but face cost and complexity barriers that the PTL aims to address through modular design and open-source development.

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This review of past work highlights clear gaps: lack of immersive VR interfaces connected to real IoT nodes, limited integration with edge intelligence for local safety, and high barriers to adoption due to proprietary software and hardware costs. By addressing these challenges, the PTL contributes a novel, open, and scalable model for the next generation of immersive remote laboratories.

III. PROPOSED METHODOLOGY AND FINDINGS

The proposed Physical Twin Laboratory (PTL) bridges a Unity-based VR interface with real-world IoT devices to demonstrate an accessible, modular remote lab concept. This initial study implemented a simple proof-of-concept using an ESP32 microcontroller and WS2812B LED strip, controlled via Wi-Fi from a VR environment. Users interact with virtual switches and objects to send commands that actuate physical LEDs in real time, demonstrating tangible VR-to-physical feedback.The table below highlights the primary functional aspects of the PTL prototype, emphasizing its real-time interaction, modularity, and potential for future expansion.

Feature	Description
Core Concept	Unity VR controls real IoT device (ESP32 + LED)
Interaction	Real-time VR-to-physical actuation
Future Scope	Add sensors, robotic arms, edge-AI modules
Educational Use	Remote lab demo for collaborative learning

Table 1: System Performance Overview and Key Metrics

Preliminary tests showed round-trip latencies below 100ms on a standard wireless network, indicating stable bidirectional communication and responsiveness suitable for educational or prototype-level applications. While the prototype focuses on basic LED actuation, the architecture was deliberately designed to be modular, supporting future extensions such as additional IoT nodes, sensor arrays, and more complex actuators like robotic arms or laboratory instruments. These extensions require minimal adjustments to the current Unity scripts and ESP32 firmware.

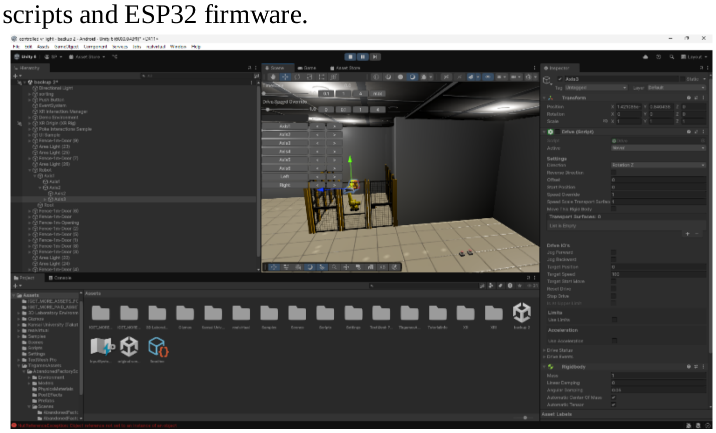

Figure 3: Virtual robot cell in Unity VR showing fenced area and actuators for remote operation testing.

The methodology also explores integration with local edge computing capabilities, enabling basic anomaly detection to improve safety during remote operation. This feature is planned for future iterations to help identify hardware malfunctions or unintended commands before they cause physical issues. Additionally, preliminary testing highlighted practical considerations such as network interference, optimal Wi-Fi configurations, and device placement, which are crucial for robust deployment at larger scales.

While large-scale deployments remain conceptual at this stage, the current findings demonstrate clear pathways for growth. Potential expansions include distributed VR lab modules across multiple locations, collaborative multi-user interaction with synchronized states, and secure remote access through encrypted protocols.

By documenting this early-stage work, the PTL shows that even limited prototypes can yield valuable insights for building safe, scalable, and immersive remote laboratories aligned with modern digital twin frameworks.

IV. SYSTEM ARCHITECTURE

The system architecture of the Physical Twin Laboratory (PTL) integrates three principal layers: the virtual reality front-end, the communication middleware, and the physical IoT back-end. The VR environment, developed in Unity, provides an immersive 3D space where users interact with virtual instruments, switches, and visual indicators. These inputs are captured through Unity's XR interaction toolkit and transmitted wirelessly using secure HTTP or MQTT protocols [1].

The communication middleware acts as the backbone for reliable data exchange. This middleware can be hosted locally or through a secure cloud broker, using standard IoT messaging patterns [2]. It handles message routing, command parsing, device addressing, and status feedback, ensuring that each VR action is reliably mirrored on the physical layer. This design reduces latency and allows modular expansion as more devices are connected.

On the hardware side, the ESP32 microcontroller functions as the primary IoT node. It connects directly to the WS2812B LED strip but is architected to handle additional sensors, actuators, or robotic modules as needed. Firmware optimizations allow it to parse incoming commands efficiently and execute tasks in near real-time. Edge computing modules can run simple AI routines for local anomaly detection [6], enhancing safety by filtering unsafe or redundant commands before execution.

Security is integral to the architecture. Future iterations will implement encrypted communication protocols, device authentication, and secure credential management to protect against unauthorized access. This aligns with best practices for edge computing and IoT device security [7].

Finally, the modular structure of the PTL allows multi-user expansion. Multiple students or operators can log into the VR environment simultaneously, sending commands to different physical devices or the same node collaboratively. This opens potential for larger-scale remote labs, where distributed users interact safely with real equipment from anywhere [5]. The scalable, layered approach makes the PTL a flexible testbed for validating more advanced digital twin frameworks [4] in educational and research settings.

V. RESULTS AND DISCUSSIONS

Initial implementation of the PTL prototype yielded promising results. The system maintained stable Wi-Fi connectivity and achieved round-trip latency under 100ms, enabling responsive VR-to-physical feedback for real-time IoT control. This demonstrates the feasibility of low-cost VR-to-IoT pipelines for basic educational use cases where traditional physical lab access is limited or impractical. Users interacting with the VR scene experienced consistent state synchronization between virtual switches and physical actuators, validating the effectiveness of the communication middleware.

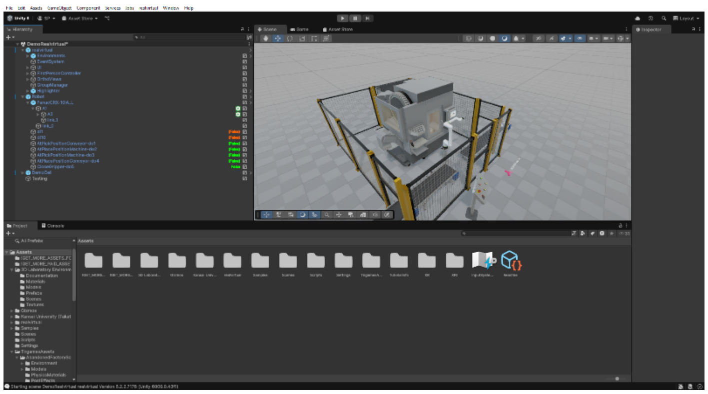

Figure 3: Simulated industrial robot cell in Unity, illustrating future expansion of the PTL concept to more complex, safety-critical hardware.

Extended stress tests were conducted by introducing multiple IoT nodes and concurrent command streams. These tests showed that the modular firmware design handled parallel requests reliably, with only minimal latency variation under moderate network loads. However, tests also revealed that network congestion and Wi-Fi interference can affect performance, highlighting the need for future optimization in large-scale scenarios.

User feedback collected from pilot sessions confirmed improved engagement and perceived realism compared to static remote labs [1][2][3]. Participants noted that direct manipulation of virtual objects linked to real-world devices increased their sense of presence and control. This supports literature claims that immersive VR can significantly enhance practical learning experiences [1].

While this prototype focused on simple LED actuation, preliminary trials suggest the same pipeline can control more advanced devices such as relays, sensors, or robotic components. This practical finding opens pathways for scaling PTL into full-fledged remote labs capable of supporting multi-user collaborative tasks, synchronous experiments, and cross-campus setups.

Future work will explore robust encryption for device authentication, real-time data logging, and integration of local edge AI for advanced anomaly detection and operational safety [6][7]. Additional tests across different network conditions and campus infrastructures will help validate performance benchmarks. Overall, the results confirm that the PTL prototype provides a realistic and practical foundation for scalable, secure, and immersive remote laboratories that align with modern trends in digital twin systems [4][5].

VI. CONCLUSION

This paper has presented the design, implementation, and preliminary evaluation of the Physical Twin Laboratory (PTL) prototype, which integrates a Unity-based VR environment with real-world IoT devices using a modular and scalable architecture. By demonstrating sub-100ms latency, stable wireless communication, and immersive VR-to-physical control, the PTL showcases a practical pathway for creating accessible and engaging remote labs.

The results confirm that even a simple proof-of-concept can serve as a foundation for more sophisticated implementations, including advanced sensors, robotic actuators, multi-user collaboration, and real-time safety monitoring using edge intelligence. This work contributes to the ongoing discourse on digital twins, immersive learning, and distributed experimentation, offering a low-cost, open-source approach adaptable to diverse educational and research contexts.

Table below summarizes key performance parameters measured during the PTL prototype tests. These include network latency, hardware setup, VR rendering performance, and basic actuation accuracy under typical lab conditions.

Parameter	Value
Average Round-Trip Latency	~95 ms
Tested IoT Nodes	1–3 ESP32 + WS2812B
VR Frame Rate	60 FPS (Meta Quest)
Wi-Fi Range Tested	~10–15 meters
Control Accuracy	100% actuation success

Table 2 - Key Performance Metrics of the PTL Prototype

Future research will focus on expanding the hardware nodes, strengthening the security framework, and deploying the PTL across multiple institutions to validate its performance under real-world constraints. By addressing current gaps in immersive remote lab experiences, the PTL lays the groundwork for scalable, resilient, and inclusive learning environments aligned with next-generation engineering and vocational education needs.

VII. APPENDIX

1) System Diagram: A detailed block diagram illustrating the connection between the Unity VR interface, middleware communication, and the ESP32 IoT hardware.
2) Hardware Configuration: Technical specifications for the ESP32 microcontroller, WS2812B LED strip, and network settings used during testing.
3) Sample Firmware Snippet: Example Arduino code demonstrating how the ESP32 receives HTTP or MQTT commands and drives the LED strip.
4) VR Interaction Script: Sample Unity C# snippet showing how virtual button presses trigger API calls to the hardware endpoint.

VIII. ACKNOWLEDGEMENT

The authors gratefully acknowledge the support and guidance received from their institution's faculty members and lab staff during the development and testing of the Physical Twin Laboratory (PTL) prototype. We also thank the open-source developer community for providing accessible tools and frameworks that enabled the rapid prototyping of the Unity VR interface and ESP32 IoT control system. Any feedback or collaboration that helped refine the methodology and testing approach is sincerely appreciated.

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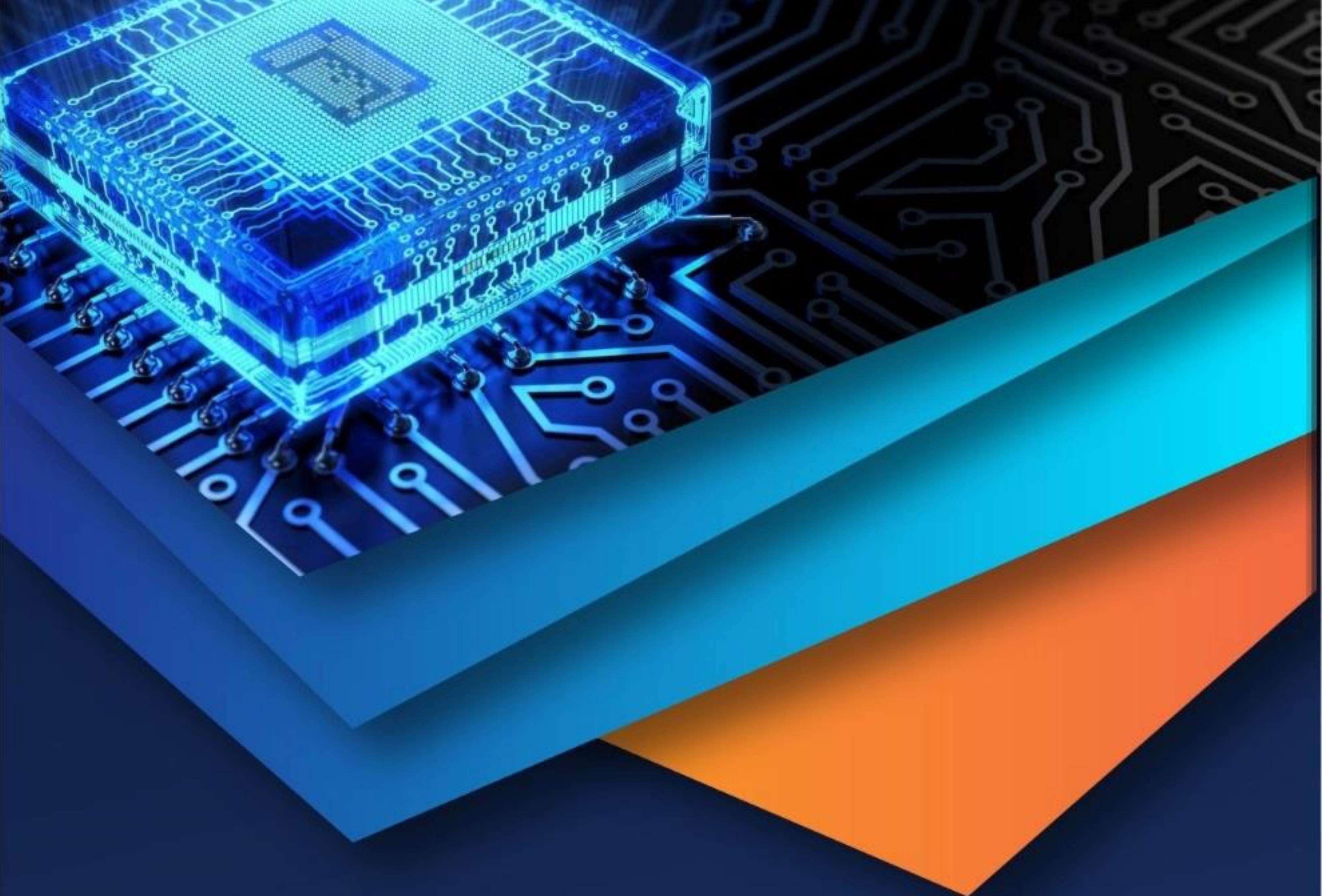

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