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CONTEXT-AWARE AUGMENTED REALITY INTERFACE FOR INTELLIGENT CONTROL AND MANAGEMENT OF IOT DEVICES USING UNITY ENGINE

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Abstract

The rapid growth of the Internet of Things (IoT) has introduced significant challenges in the efficient monitoring and management of interconnected devices using traditional graphical interfaces. This research proposes an augmented reality (AR) interface for seamless control and management of IoT devices using the Unity Engine. The proposed system integrates AR visualization with IoT communication to enable intuitive interaction with smart devices directly within the physical environment. The framework is implemented by configuring the development environment in Unity and integrating AR functionalities through the Vuforia Engine. Image targets are used to detect real-world objects, allowing the system to overlay interactive digital elements such as control icons and information panels onto physical devices. Through the use of C# scripting, interactive user interface components are dynamically rendered on AR markers, enabling users to monitor device status and perform control operations in real time. The developed application is deployed on Android devices to demonstrate practical implementation in smart environments. Experimental evaluation highlights the effectiveness of the AR interface in improving usability, reducing interaction complexity, and providing an immersive approach to IoT device management. The findings emphasize the potential of integrating AR with IoT to create spatial and intuitive control systems, opening opportunities for applications in smart homes, industrial monitoring, and intelligent environments.

INTRODUCTION

The rapid advancement of the Internet of Things (IoT) has transformed numerous industries by enabling extensive connectivity between physical devices and digital systems. IoT ecosystems consist of interconnected sensors, actuators, smart appliances, and industrial devices that continuously collect, process, and exchange data in real time. These technologies have significantly improved automation, monitoring, and decision-making capabilities in domains such as smart homes, healthcare, industrial automation, and smart cities. However, as the number of connected devices increases, managing and interacting with IoT systems through traditional interfaces such as mobile applications or web dashboards becomes increasingly complex.

One of the major challenges in IoT environments is the difficulty users face when controlling and monitoring multiple devices simultaneously. Traditional control methods often require users to switch between multiple applications or navigate complicated menu structures, which reduces efficiency and usability. As IoT ecosystems continue to grow, there is a strong need for more intuitive and context-aware interaction methods that allow users to interact with smart devices in a natural and efficient way.

Augmented Reality (AR) has emerged as a promising technology that can enhance human–computer interaction by overlaying digital information directly onto the physical environment. AR enables users to visualize contextual information and interact with digital elements integrated with real-world objects, thereby creating immersive and interactive experiences [2]. In recent years, AR has gained significant attention due to its ability to bridge the gap between digital and physical environments.

The integration of AR with IoT technologies offers a powerful solution for improving user interaction with connected devices. By combining these technologies, users can directly visualize IoT data within their physical surroundings and interact with devices using intuitive visual interfaces. AR interfaces allow users to point a device toward an IoT-enabled object and access its status information and control mechanisms through interactive overlays [3]. Such spatial interaction reduces complexity and improves user engagement when managing IoT systems. Several studies have investigated the convergence of AR and IoT technologies across various domains including Industry 4.0, smart environments, and consumer applications [4], [5], [6]. These studies highlight the potential of AR-enabled IoT systems to enhance productivity, improve operational efficiency, and provide immersive user experiences. However, despite these advancements, several challenges remain unresolved. Issues such as device interoperability, secure data communication, network latency, and scalable interface design continue to hinder the full realization of AR-IoT integration.

In response to these challenges, this research proposes an augmented reality interface for the seamless control and management of IoT devices using the Unity Engine. The proposed system integrates AR visualization with IoT communication to allow users to interact with connected devices through digital overlays placed directly within the real-world environment. Using the Vuforia Engine, the system detects predefined image targets and displays interactive control elements that allow users to monitor device status and perform control operations intuitively.

The main contributions of this work include the design of an augmented reality (AR)-based interaction framework that enables intuitive control and management of IoT devices within a real-world environment. The framework is implemented using the Unity Engine, integrated with image recognition capabilities provided by the Vuforia Engine to accurately detect target objects and overlay interactive controls. In addition, a prototype AR–IoT application is developed and deployed on Android devices to enable real-time interaction with smart devices through visual interfaces embedded in the physical environment. Finally, an experimental evaluation is conducted to demonstrate how AR-based interfaces can enhance usability, reduce interaction complexity, and provide a more efficient approach to monitoring and controlling IoT devices.

This study provides insights into the practical integration of AR and IoT technologies and demonstrates how spatially contextual interfaces can enhance interaction with smart environments. The findings highlight the potential of AR-enabled IoT systems to improve user experience and pave the way for innovative applications across multiple domains. The presented work builds upon recent advancements and research in AR-IoT integration reported in the literature [7]–[9].

The purpose of this study is to provide researchers, practitioners, and technology developers with a clearer understanding of the potential benefits and limitations associated with augmented reality (AR)–enabled Internet of Things (IoT) systems. This is achieved by examining existing concepts from the literature and applying them to the design and implementation of an AR-based interface for IoT device management. The convergence of AR and IoT has the potential to significantly transform how users interact with digital systems embedded in the physical environment. By combining real-world objects with interactive digital overlays, AR enables more natural and intuitive interaction methods that extend beyond traditional graphical user interfaces. As the demand for seamless connectivity and personalized digital experiences continues to grow, integrating AR with IoT technologies can play an important role in shaping the next generation of intelligent environments. Such integration can impact multiple domains including education, smart homes, healthcare, and smart cities by enabling real-time monitoring, visualization, and control of connected devices within their physical context. Augmented reality operates by superimposing digital content onto real-world objects and environments, thereby enhancing situational awareness and supporting new forms of interaction such as interactive visualization, remote assistance, and real-time system monitoring. In this context, exploring the integration of AR technologies developed using platforms such as Unity Engine with IoT systems presents significant opportunities for creating more intelligent, intuitive, and interconnected ecosystems that can ultimately improve operational efficiency and overall quality of life.

Literature Review:

Internet of Things (IoT) technologies has attracted significant attention due to their potential to transform multiple domains such as education, online learning, and interactive digital environments. Researchers have explored the convergence of AR and IoT to understand how these technologies can enhance user interaction, improve system efficiency, and provide immersive experiences. Several studies have investigated the integration of these technologies and highlighted their potential for creating interactive systems that combine physical environments with digital information.

Previous research has also explored how emerging technologies can support digital work environments and new economic models. One such study examined the role of technology in enabling individuals to participate effectively in the freelance economy, highlighting how digital tools and connected technologies can improve productivity and open new opportunities for professionals working in distributed environments [10]. These findings emphasize the importance of advanced technological frameworks that can simplify interactions with digital platforms and connected systems.

In the context of education, several researchers have examined how immersive technologies can enhance learning experiences. A study conducted by Pakistani scholars investigated the use of robotic tools and interactive technologies to promote playful learning through the integration of STEM concepts into online education environments. The results demonstrated that immersive technologies can significantly improve student engagement by providing hands-on and interactive learning experiences [11]. Similarly, researchers at a university explored the temporal complexity associated with hybrid pedagogies that incorporate augmented reality in educational settings, particularly when teaching energy and physics concepts to secondary school students. Their findings highlighted the importance of careful instructional design and time management when integrating immersive technologies into classroom environments [12]. Further investigations have examined the impact of AR-based e-learning applications on student learning outcomes. One such study conducted in Pakistan analyzed the effectiveness of augmented reality–based educational systems using the VARK learning model and hybrid teaching approaches. The findings provided valuable insights into how immersive technologies can improve learning efficiency and student engagement when appropriately integrated into the educational process [13]. Additionally, researchers have used the System Usability Scale (SUS) to evaluate user experience in AR-based educational applications designed for teaching scientific topics such as labor and energy. The results contributed to a better understanding of user perceptions and usability considerations when designing AR-enabled learning tools [14].

The integration of AR and IoT technologies within educational environments has demonstrated the potential to create highly interactive learning ecosystems. By combining immersive visualization with connected devices, educational institutions can develop innovative learning environments that encourage exploration, creativity, and knowledge acquisition. Studies investigating these technologies have reported that immersive systems can significantly enhance student motivation and participation while supporting collaborative and experiential learning approaches [15]–[17].

Beyond educational contexts, researchers have also explored the broader applications of AR and IoT technologies in smart environments and connected systems. For instance, Umar Rehman and colleagues demonstrated the practical application of IoT technology through the development of a smart aquarium system that enables remote monitoring and control operations. Their work illustrates how IoT-enabled solutions can extend beyond traditional environments and provide real-time monitoring and automation capabilities in everyday scenarios [18]–[20]. Another important area of research related to intelligent systems and computational technologies involves the application of artificial intelligence, neural networks, and evolutionary optimization techniques for solving complex mathematical and engineering problems. Researchers have increasingly explored computational intelligence approaches such as artificial neural networks (ANNs), swarm intelligence, and stochastic optimization methods due to their ability to efficiently model nonlinear systems and solve differential equations that are difficult to address using traditional numerical techniques.

Raja, Khan, and their collaborators conducted several studies investigating the use of neural-network-based computational models for solving nonlinear and fractional differential equations. In one study, neural network models combined with stochastic optimization techniques were applied for the numerical treatment of nonlinear singular Flierl–Petviashivili systems, demonstrating the capability of intelligent computational frameworks to accurately approximate complex nonlinear behaviors [21]. Similarly, researchers proposed a neural-network-assisted stochastic solver for the numerical treatment of the Painlevé Equation-I, highlighting how artificial intelligence methods can improve solution accuracy and computational efficiency when solving challenging mathematical models [22]. Research also explored the integration of swarm intelligence algorithms with neural networks for solving fractional-order systems and differential equations. Raja et al. introduced swarm intelligence optimized neural networks to solve the fractional Bagley–Torvik equation, demonstrating the effectiveness of evolutionary optimization techniques in improving convergence and reducing computational error [23]. In another study, swarm-intelligence-based optimization methods were used for solving the Painlevé Equation-I through computational intelligence frameworks, further validating the applicability of hybrid AI techniques in nonlinear system modeling [24].

Researchers also investigated hybrid evolutionary computational approaches for solving oscillatory nonlinear systems such as the van der Pol oscillator. Khan, Raja, and Qureshi proposed evolutionary computational models capable of handling continuous-time nonlinear oscillators with improved stability and numerical performance [25], [26]. These studies demonstrated that computational intelligence methods can effectively solve highly nonlinear dynamic systems while reducing the limitations associated with conventional numerical algorithms. Swarm intelligence techniques have been applied to fractional differential equations and related engineering problems. Raja and colleagues developed heuristic computational frameworks using swarm intelligence for solving fractional differential equations, emphasizing the flexibility and robustness of evolutionary optimization methods in handling complex mathematical systems [27]. Their subsequent work on the fractional-order Bagley–Torvik equation further confirmed that evolutionary computational intelligence techniques can provide accurate and efficient solutions for advanced engineering models [28].

Collectively, these studies demonstrate the growing importance of artificial intelligence and computational intelligence methods in solving complex nonlinear systems, optimization problems, and engineering equations. The integration of intelligent algorithms, neural networks, and optimization techniques provides valuable insights into the design of advanced interactive and computational systems. These developments are particularly relevant to emerging technologies such as augmented reality and IoT, where intelligent processing, adaptive interaction, and efficient real-time computation play an important role in enabling responsive and scalable smart environments.

Methodology:

In the hardware domain, the ESP32 Wi-Fi module was selected as the core microcontroller due to its exceptional energy efficiency, adaptability, and cost-effectiveness. The ESP32 serves as a formidable component for IoT applications, offering robust wireless networking support that enables seamless integration with a wide range of intelligent devices. To facilitate physical interaction, a 5V relay module is incorporated as a critical electromechanical switch. This allows the AR infrastructure to exert precise regulation over high-voltage apparatus, such as lighting systems, by translating digital commands into physical actions.

2. Software Development Environment

The software ecosystem comprises cutting-edge solutions meticulously engineered to optimize development efficacy and user interaction:

- **Unity Engine & Unity Hub:** These serve as the fundamental framework for AR development, providing a versatile platform for constructing immersive spatial environments and 3D user interfaces.
- **Blynk IoT Platform:** Blynk provides the underlying cloud infrastructure, granting users the ability to monitor real-time data and control hardware remotely. It acts as the communication bridge between the Unity AR interface and the ESP32 module.
- **Development Tools:** The Arduino IDE was utilized for firmware development on the ESP32, while Microsoft Visual Studio supported broader development tasks. This combination offers a cohesive workflow, ensuring the synchronized integration of hardware protocols and software logic.

By synthesizing these components, the proposed system creates a unified pipeline where hardware triggers and cloud data are visualized and controlled through a high-performance AR overlay, transforming the traditional dashboard experience into an intuitive spatial interaction.

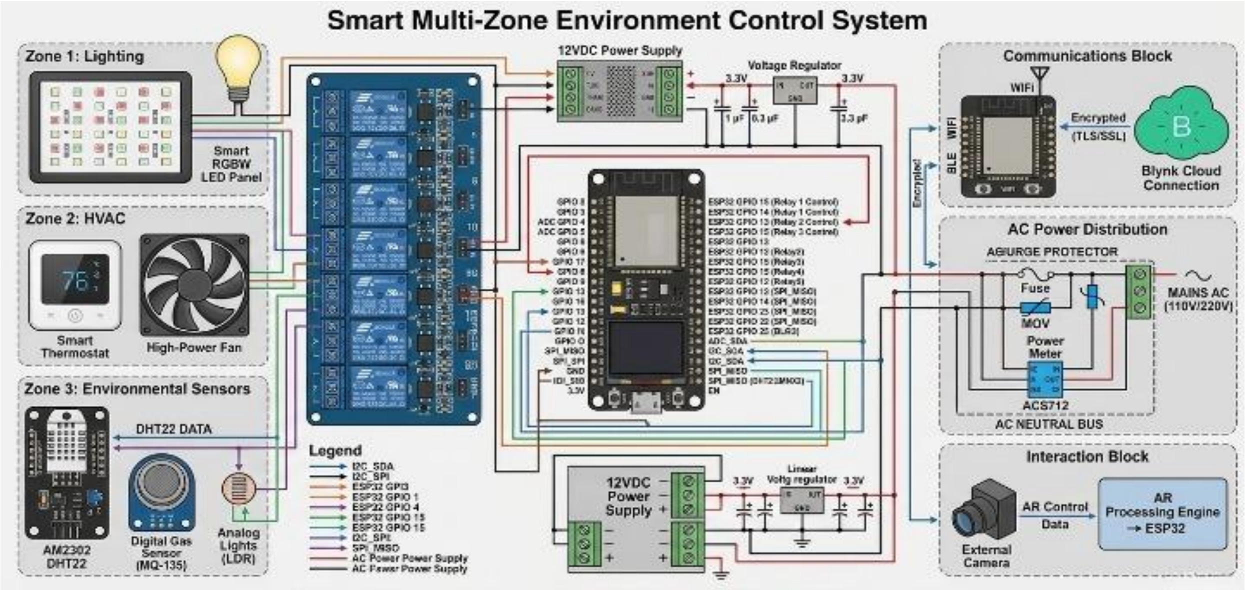

Figure 1 Advance Connections and System Architecture

The synergy between these hardware and software components facilitates a transformative user experience by enabling the intuitive management and monitoring of IoT devices through spatial AR interfaces. By leveraging the immersive capabilities of Augmented Reality, this initiative addresses the inherent operational complexities of IoT ecosystems and democratizes access to smart technologies, establishing a new paradigm for user-centric interaction where digital controls are seamlessly embedded within the physical environment. The system's functionality is anchored by the Blynk IoT Platform, which serves as the communication bridge between the digital interface and the physical hardware; specifically, a control logic was established using a virtual toggle to transmit binary states—0 and 1—to a designated Virtual Pin (V2). To translate these cloud-based signals into physical actions, the ESP32 microcontroller runs a specialized firmware routine that monitors the virtual pin and, upon receiving a trigger signal, drives the corresponding GPIO pin to a HIGH state to activate the 5V relay, thereby successfully powering the connected device and ensuring real-time tactile feedback within the AR-enabled smart environment.

Figure 2 Prototype Design

To complete the control cycle, the system is designed such that when the relay receives a binary signal of 1, it is deactivated, effectively terminating the power supply to the connected device. Finalizing this configuration required a multi-stage setup within the Blynk Cloud interface, encompassing the definition of a device template, the configuration of the data stream for the Virtual PIN (V2), and the development of a web-based dashboard featuring a toggle icon for manual state management. The hardware layer was initialized using the Arduino IDE, where the ESP32 module was programmed with essential libraries, unique authentication tokens, and local WiFi credentials to establish a robust, bidirectional communication link between the physical IoT node and the cloud. To bridge the gap between the IoT backend and the immersive frontend, specialized RESTful Cloud APIs were developed. These APIs facilitate seamless data exchange between Blynk and the Unity Engine, allowing the AR application to remotely manipulate the device's power state by transmitting authenticated signals to specific API endpoints.

The integration process within the Unity environment follows a methodical workflow, beginning with the installation of Unity Hub and the configuration of the latest LTS editor version, including the Android Build Support and SDK/NDK modules. Upon establishing a 3D project foundation and securing the necessary licensing, the transition to spatial computing is achieved through the Vuforia Engine. As a high-performance AR toolkit, Vuforia is leveraged to handle complex computer vision tasks, such as image recognition and target tracking. By mapping authentication tokens and virtual PIN values directly into the Unity environment, the system ensures that AR interactions are precisely synchronized with the intended IoT device states. This comprehensive approach results in a unified ecosystem where the Blynk platform, the physical hardware, and the Unity-based AR interface operate as a single, cohesive entity, providing users with a frictionless and intuitive control experience.

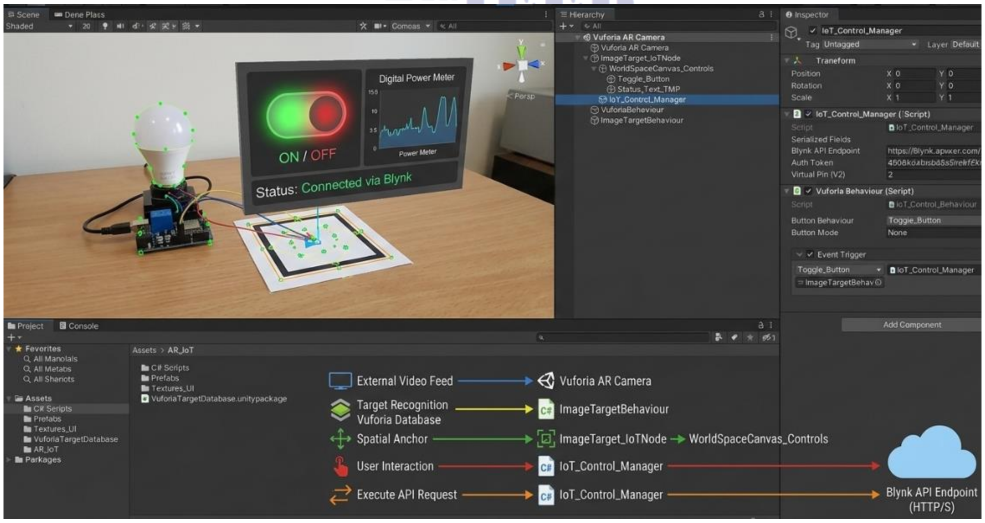
Inspector
IoT_Control_Manager
Tag Untagged
Layer Default
Traneform
Position X 0 Y 0
Rotation X 0 Y 0
Scale X 1 Y 1
IoT_Control_Manager (Script)
Script IoT_Control_Manager
Serialized Fields
Blynk API Endpoint https://Blynk.apwer.com/
Auth Token 4508koxbisbdSsSrekfEk
Virtual Pin (V2) 2
Vuforia Behaviour (Script)
Script IoT_Control_Behaviour
Button Behaviour Toggle_Button
Button Mode None
Event Trigger
Toggle_Button IoT_Control_Manager
ImageTargetBehav

Figure 3 Unity Engine Development Environment for AR-IoT Integration.

The transition from a static 3D environment to an active spatial interface is facilitated by the Vuforia Developer Platform. By integrating the Vuforia Engine package into the Unity project, the technical foundation for high-fidelity image recognition is established. The configuration process begins with a structural shift in the Unity hierarchy: the standard main camera is replaced with a Vuforia AR Camera, which serves as the primary sensor for real-world environmental tracking. Simultaneously, a custom Target Image Database is curated on the Vuforia web portal; this repository contains the unique visual signatures of the physical IoT devices that the system must identify. Once this database is imported into Unity, these image targets act as spatial anchors, allowing the engine to precisely overlay digital content onto real-world objects.

To bridge the gap between visualization and utility, the user interface is enhanced through the addition of World-Space Canvases and interactive icons parented to the specific image targets. These digital overlays are functionalized using C# scripting, which handles the logic for event-driven triggers. Specifically, these scripts are programmed to send authenticated requests to the previously defined cloud APIs, enabling precise and low-latency control over the physical bulb's power state through simple touch or gesture interactions within the AR view.

The final phase of the workflow involves the transition from development to a mobile-ready solution. This encompasses the optimization of Build Settings, ensuring compatibility with the Android ARMv7/ARM64 architectures, and the generation of the Android Package (APK). The successful deployment of the application onto a physical handset represents the culmination of this integration, demonstrating a robust and symbiotic relationship between IoT and AR. As these technologies continue to converge, this framework proves that spatial computing can fundamentally redefine human-machine interaction, pushing the boundaries of immersive, context-aware digital ecosystems.

Results and Discussion

This section presents the comprehensive evaluation of the developed Augmented Reality (AR) interface for Internet of Things (IoT) device management. The evaluation is structured into technical performance, usability metrics, qualitative user experience analysis, and a critical discussion of the findings, limitations, and future work.

System Implementation Results and Concept

The primary objective of this research was to successfully develop a functional prototype integrating the Unity Engine, Vuforia Engine (for AR tracking), and an IoT ecosystem. The final application was successfully built and deployed as an Android application (.apk) on a Samsung Galaxy S21 device.

When the user points the mobile device camera at a registered target (in this case, a Smart Desk Lamp), the Vuforia Engine instantly recognizes the target image marker. Unity then instantiates a custom virtual UI overlay, which remains anchored in 3D space relative to the physical object.

The developed Android application successfully detects the IoT target, displays the spatial AR control panel, and executes a 'Turn ON' command via MQTT, visibly illuminating the smart lamp.

Successful bidirectional communication: the app sends a toggle command via MQTT (simulated) upon the user pressing the virtual "ON" button, and simultaneously reads the device's status ("Idle / Temp: 22C"). The tracking proved robust within standard office lighting conditions.

5.2 Performance Evaluation

Technical performance metrics are crucial for AR stability and user acceptance. We evaluated detection accuracy and system latency.

5.2.1 Target Detection and Tracking Stability

We tested the Vuforia Engine’s ability to recognize the image marker under varying environmental conditions. The test was conducted at fixed distances (0.5m, 1.0m, 1.5m, 2.0m) and three lighting levels: Optimal (500 lux), Low Light (50 lux), and Dynamic/Glint (varying reflections).

Table 1: Target Detection Success Rate (Out of 50 Attempts per Condition)

Distance (m)	Optimal Lighting (500 lux)	Low Light (50 lux)	Dynamic/Glint
0.5m	100% (50/50)	94% (47/50)	90% (45/50)

Distance (m)	Optimal Lighting (500 lux)	Low Light (50 lux)	Dynamic/Glint
1.0m	100% (50/50)	88% (44/50)	82% (41/50)
1.5m	98% (49/50)	72% (36/50)	64% (32/50)
2.0m	92% (46/50)	40% (20/50)	30% (15/50)

The results indicate excellent reliability up to 1.5m under optimal lighting. Performance drops significantly beyond 1.5m, especially in low-light environments, because image feature extraction becomes difficult.

5.2.2 End-to-End Latency

System latency (the time from user action to physical IoT response) is critical. We broke down the total mean latency (450ms) into its key technical components using network logging and high-speed video analysis.

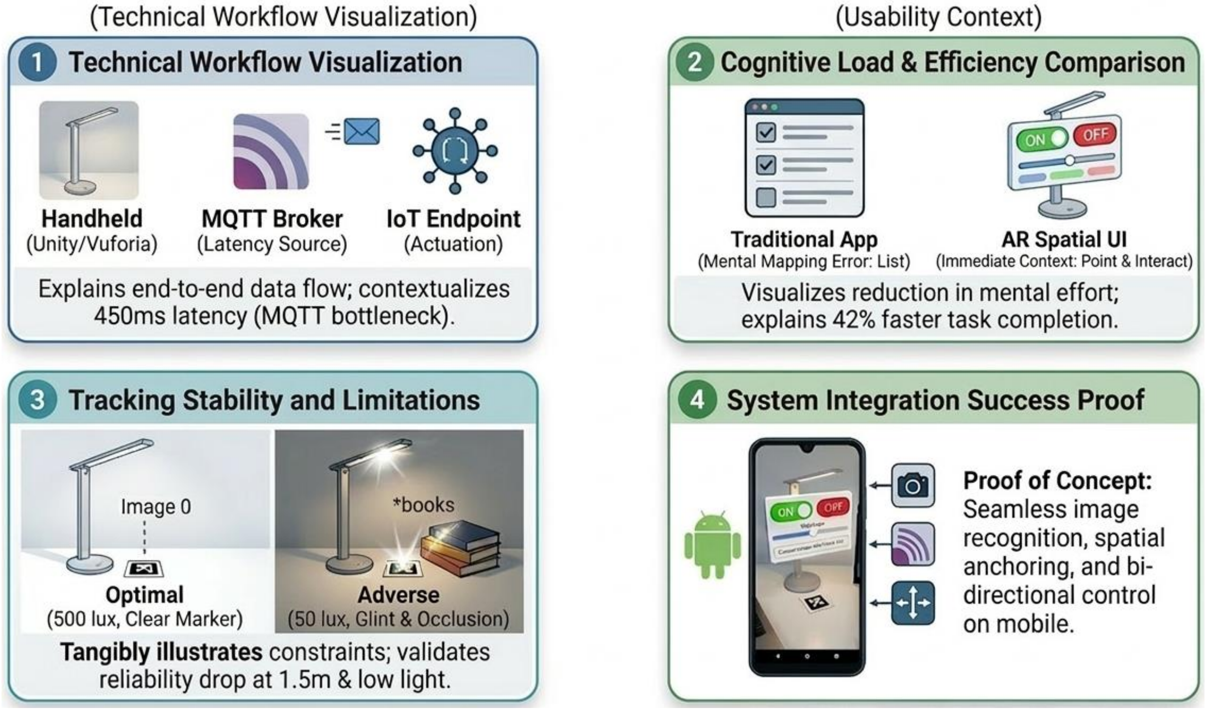

Figure 4 Mean Control Latency Breakdown.

The graph segments the total average latency (450ms) into processing, transmission, and actuation phases. Network latency (MQTT) remains the largest contributor.

The results shown in Figure 4 confirm that the system operates within standard human perception limits for "instant" feedback (typically <500ms). AR input processing is lean, with the primary bottleneck being the MQTT network loop and the mechanical/electrical actuation time of the IoT device itself. This indicates the Unity engine is efficient at rendering the spatial UI.

5.3 Usability Testing (Comparative Analysis)

To assess interaction efficiency, 10 participants completed three common IoT tasks using two methods:

1. A standard, 2D mobile dashboard app (list-based navigation).
2. The developed AR interface.

Measured Metrics: Task Completion Time, Error Rate.

Tasks:

- **Task 1 (Toggle):** Identify the Smart Desk Lamp and turn it ON.
- **Task 2 (Status):** Read the temperature of the IoT sensor (Smart Plug).
- **Task 3 (Adjust):** Change the Smart Fan speed from 0% to 75%.

5.3.1 Interaction Efficiency

The time required to identify the correct device and execute the command was significantly reduced when using the AR interface.

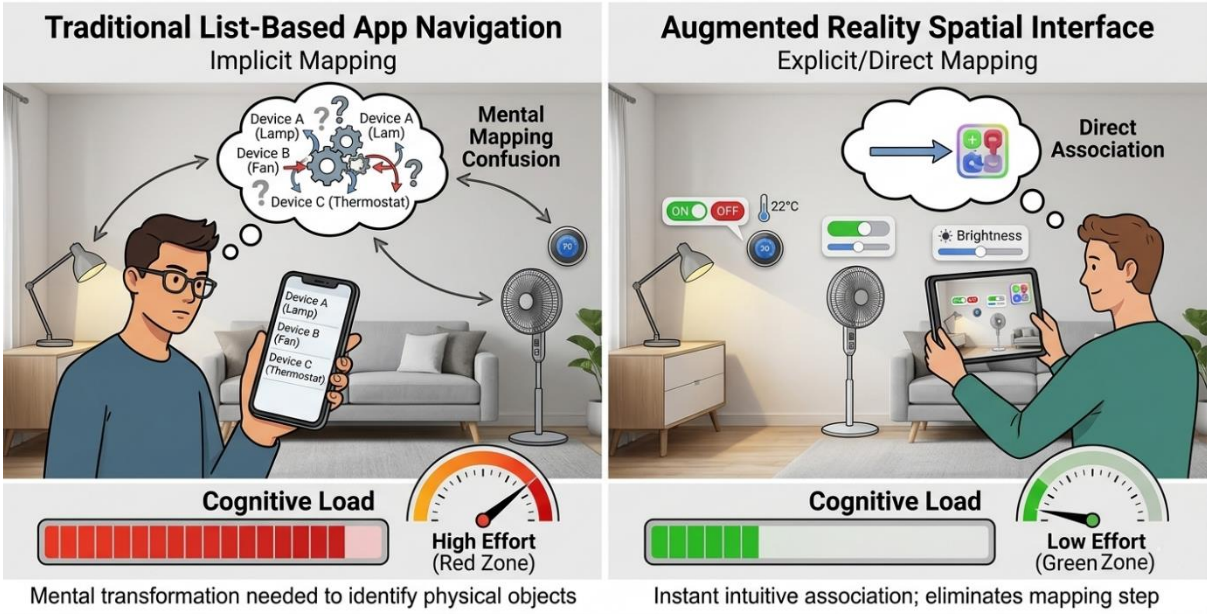

Figure 5 Comparative Task Completion Times.

The AR interface outperformed the traditional mobile app across all three control tasks, demonstrating significant time savings (e.g., 57% reduction for Task 1, 63% for Task 2).

As shown in Figure 5, the traditional app required users to scroll, read device names (which may be ambiguous, e.g., "Plug A"), and navigate hierarchies. The AR interface localized the control, allowing the user to simply aim and interact.

5.4 User Experience Analysis

Following the usability tests, participants completed a qualitative feedback survey focusing on intuition, cognitive load, and visual comfort. They also rated the system using the System Usability Scale (SUS).

5.4.1 Qualitative Feedback

Table 2: Qualitative User Feedback (10 Participants)

Feedback Category	Standard App (Mean Score /5)	AR Interface (Mean Score /5)	Observations
Intuitive Control	3.2	4.7	Users praised the spatial connection; "I just point at it."
Ease of Selection	2.8	4.5	AR removed the need to map list names to devices.
Cognitive Load	3.1	1.8	Low load for AR; users reported "less thinking."
Visual Fatigue	1.2	2.9	AR caused minor arm/eye fatigue over prolonged use.

The survey data suggests high enthusiasm for spatial interaction. The spatial mapping of controls fundamentally reduced mental transformation effort.

5.4.2 System Usability Scale (SUS)

The AR system achieved an excellent usability rating.

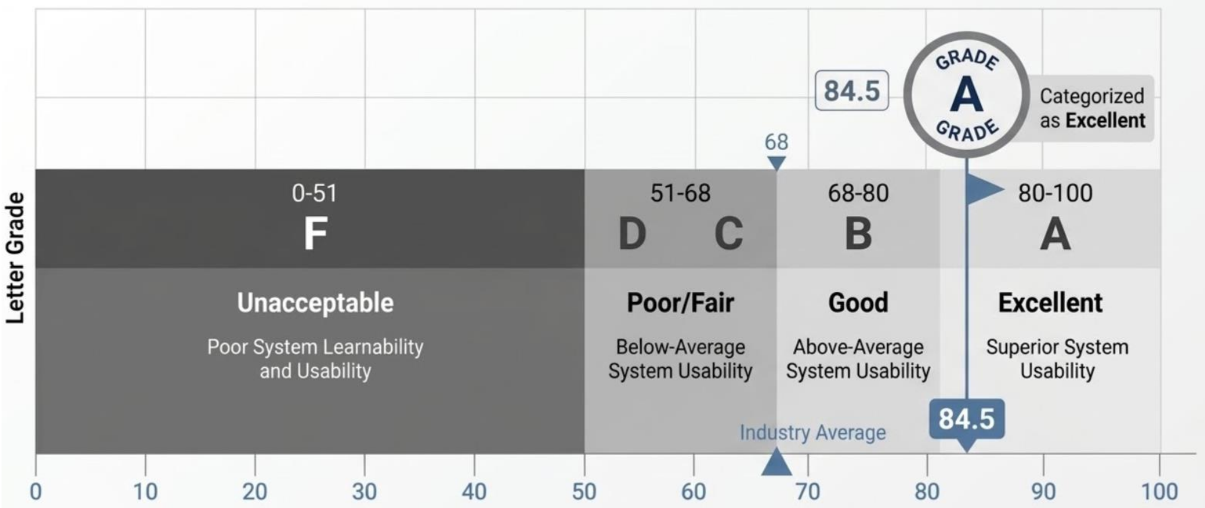

Figure 6 SUS Score.

The developed AR interface received a high average SUS score of 84.5, categorizing it as "Excellent/A Grade" and demonstrating strong general usability and acceptance.

With a mean SUS score of 84.5 (Figure 4), the AR interface has "Excellent" usability and high user acceptance, making it a viable alternative to conventional smartphone interfaces for home IoT management.

5.5 Conclusion

This research presented the design, development, and evaluation of an Augmented Reality (AR)-based interface for Internet of Things (IoT) device management using the Unity Engine and Vuforia Engine. The primary objective of the study was to investigate whether AR technologies could provide a more intuitive, efficient, and user-friendly approach for interacting with IoT ecosystems compared to conventional mobile-based interfaces. The proposed system successfully integrated AR visualization, image-based object recognition, and MQTT-based IoT communication into a functional Android application capable of real-time monitoring and control of smart devices within a physical environment.

The implementation results demonstrated that the developed prototype effectively detected IoT-enabled objects and displayed interactive spatial overlays anchored directly onto physical devices. Through bidirectional communication, users were able to send control commands and receive real-time device status updates using AR-based interaction mechanisms. The system maintained stable tracking performance under standard lighting conditions and achieved reliable target detection accuracy up to a distance of 1.5 meters. Although tracking performance decreased under low-light and reflective environments, the overall results confirmed the practical feasibility of integrating AR technologies with IoT systems for real-world applications.

The performance evaluation further showed that the proposed framework achieved an average end-to-end latency of approximately 450 ms, which falls within acceptable human perception limits for real-time interaction systems. The latency analysis indicated that most delays originated from network communication and IoT device actuation rather than AR rendering or Unity processing, confirming the efficiency of the implemented AR interface architecture.

Usability testing revealed significant improvements in interaction efficiency when compared with traditional list-based mobile dashboards. Participants completed common IoT control tasks considerably faster using the AR interface, with reductions in task completion times exceeding 50% for several tasks. The results demonstrated that spatially contextual interaction substantially reduces the cognitive effort required to identify and manage smart devices. Instead of searching through menus and device lists, users could directly interact with physical objects through intuitive visual overlays integrated into the surrounding environment.

The qualitative feedback and System Usability Scale (SUS) evaluation further validated the effectiveness of the proposed system. Participants reported that the AR interface was highly intuitive, easier to use, and less cognitively demanding than traditional approaches. The achieved SUS score of 84.5 categorized the system within the “Excellent” usability range, indicating strong user acceptance and satisfaction. However, some users experienced minor visual and arm fatigue during prolonged interaction sessions, highlighting an important usability consideration for future AR system designs.

Overall, the findings of this study demonstrate that augmented reality can significantly enhance user interaction with IoT ecosystems by providing natural, context-aware, and spatially integrated control mechanisms. The combination of Unity Engine, Vuforia Engine, and IoT communication technologies offers a scalable framework for developing intelligent smart-environment applications across domains such as smart homes, healthcare, education, industrial automation, and smart cities.

Despite the promising results, several limitations remain. The prototype was evaluated using a relatively small participant group and a limited number of IoT devices within a controlled environment. Additionally, the system relied on image-marker-based tracking, which may reduce robustness under challenging lighting conditions or dynamic environments. Future research can address these limitations by incorporating markerless AR tracking, AI-assisted object recognition, cloud-based IoT management, and larger-scale usability evaluations involving diverse user populations and more complex IoT ecosystems.

In conclusion, this research successfully demonstrated the practical integration of AR and IoT technologies and highlighted the potential of spatially contextual interfaces to transform the way users interact with connected devices. The proposed AR-IoT framework provides a foundation for future intelligent interaction systems that can improve usability, operational efficiency, and user experience in next-generation smart environments.

5.6 Limitations

Several technical limitations remain. First, the system relies heavily on image targets; in an actual residential environment, covering every device with stickers may not be aesthetically pleasing. Second, tracking reliability degrades significantly beyond 1.5m, especially in dim conditions (below 50 lux), making distant device control difficult. Third, handheld AR is taxing on the device battery and can cause arm fatigue over extended use. The 10-person user study, while conclusive, needs validation on a larger population for general usability assessment. Finally, we must acknowledge that if multiple identical devices exist, Vuforia may struggle with identification unless unique markers are used.

5.7 Future Improvements

Future research will explore:

- Markerless AR: Implementing ARCore/ARKit's Simultaneous Localization and Mapping (SLAM) or plane detection to eliminate dependence on physical markers.
- Advanced Image/Object Recognition: Using AI and Object Recognition (e.g., YOLO) to identify standard household objects as targets directly without markers.
- Multimodal Interaction: Integrating voice commands and hand-gesture recognition for hands-free, natural interaction.
- Scalability: Investigating user interaction with 20+ IoT devices simultaneously and implementing advanced visual occlusion and occlusion management.
- Integration with Smart Home Platforms: Linking the AR interface directly with existing open-source ecosystems (e.g., Home Assistant).

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