VTE VOCATION, TECHNOLOGY & EDUCATION

ORIGINAL ARTICLES

VRIOTS: Design and development of an immersive virtual reality platform for Internet of Things education

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ABSTRACT

The integration of virtual reality (VR) into educational settings has shown significant potential in enhancing learning experiences, particularly in complex fields such as Internet of Things (IoT). This paper presents the design and development of VRIOTS, a VR-based learning platform aimed at providing students with hands-on experience in IoT projects without the need for expensive physical hardware. The platform simulates real-world IoT environments, allowing students to interact with virtual devices and systems, thereby improving their understanding, retention, and practical skills. Using an Agile development methodology and iterative user testing with 35 participants, we evaluated learning engagement through a user engagement scale and pre-post knowledge tests. The findings demonstrated significant improvements in knowledge retention, learning engagement, and task completion rate. Moreover, it was shown that VR-based learning not only enhances knowledge retention and student learning engagement but also makes IoT education more accessible and cost-effective. This research highlights the importance of VR in overcoming the limitations of traditional learning methods and preparing students for future careers in the IoT and related fields.

Key words: Internet of Things, virtual reality environment, visualization, spatial visualization ability

INTRODUCTION

The Internet of Things (IoT) is a rapidly growing field that integrates physical devices with internet connectivity to enable smart systems. However, the high cost of IoT hardware and lack of access to practical learning resources poses significant challenges for students, particularly in resource-constrained educational institutions. This limitation critically hinders the objectives of the Malaysian National technical and vocational education and training (TVET) Policy 2024 (National TVET Council Secretariat, 2024), which prioritizes the development of a digitally competent workforce capable of driving the Fourth Industrial Revolution (IR 4.0). Specifically, Malaysian Polytechnic students require immersive, hands-on training to bridge the skills gap and secure high-demand roles as IoT system integrators, network specialists, and smart industry technicians. Traditional theoretical learning methods often fail to provide the hands-on experience necessary for students to fully grasp IoT concepts. To address these challenges, this study proposes VRIOTS, a virtual reality (VR)-based platform that simulates IoT environments, allowing students to interact with virtual devices and systems in a cost-effective and immersive manner.

Problem statement

A key limitation in IoT education is the overreliance on

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theoretical instruction without sufficient hands-on practical experience, which hinders students' ability to apply concepts in real-world scenarios. In addition, the high cost of IoT hardware including sensors, development kits, and other essential components imposes significant financial burdens on educational institutions, limiting accessibility and scalability. This financial barrier exacerbates inequities in learning opportunities, particularly for students and institutions with constrained resources, ultimately restricting the widespread adoption of comprehensive IoT training programs. Addressing these challenges requires innovative, cost-effective solutions to bridge the gap between theory and practice while ensuring equitable access to IoT education.

Objectives

This study aims to (1) design and develop VRIOTS, an immersive VR platform that simulates real-world IoT environments to provide accessible, hands-on learning experiences without physical hardware constraints; (2) evaluate the platform's effectiveness in enhancing knowledge retention and practical skills through pre-post knowledge tests and user engagement metrics; (3) assess the impact of VR-based learning on student engagement and task performance compared to traditional methods; and (4) establish a scalable, cost-effective model for IoT education that bridges the gap between theoretical instruction and real-world application. By addressing these objectives, this research seeks to validate VR as a transformative tool for technical education while providing empirical evidence of its benefits in improving learning outcomes and career readiness in the IoT field.

Research questions (RQs)

Based on the objectives, this study addresses the following RQs. RQ1: How can an immersive VR environment be designed to accurately simulate IoT device configuration and interaction? RQ2: To what extent does the VRIOTS platform support student engagement and perceived understanding of IoT concepts? RQ3: What usability challenges and user experiences are associated with implementing VR in a technical curriculum?

LITERATURE REVIEW

Virtual reality in education

VR has emerged as a transformative tool in education, offering immersive and interactive learning experiences that traditional methods cannot provide. According to Marougkas *et al.* (2023), VR enables learners to comprehend complex concepts more efficiently by providing realistic simulations and virtual environments. VR technology has been successfully applied in various educational contexts, from virtual field trips to complex technical simulations, enhancing student engagement and learning outcomes. The immersive nature of VR allows students to explore and interact with virtual objects in ways that are not possible in a traditional classroom setting, leading to a deeper understanding and retention of knowledge. Moreover, Huang *et al.* (2010) highlighted that VR can create a sense of presence, through which students feel as though they are physically present in the virtual environment. This sense of presence is crucial for experiential learning, as it allows students to practice skills and apply knowledge in a safe and controlled environment. For instance, medical students can perform virtual surgeries and engineering students can simulate complex machinery operations. In the context of IoT education, VR can provide students with the opportunity to interact with virtual IoT devices, configure them, and observe their behavior in real time, thereby bridging the gap between theory and practice.

IoT in education

IoT is a critical area of study in higher education as it integrates physical devices with internet connectivity to support various human activities (Kumar & Al-Besher, 2022). Its applications in numerous fields, including smart homes, healthcare, agriculture, and industrial automation, make IoT technology competencies an essential skill for future professionals. However, the high cost of IoT hardware and lack of practical learning resources often hinder students' ability to gain hands-on experience. Traditional teaching methods, which rely heavily on lectures and theoretical content, fail to provide the practical skills needed to work with IoT systems. To address these challenges, online platforms such as Wokwi have been developed to provide virtual environments for IoT programming. According to Tuyen (2022), Wokwi allows students to code and simulate IoT projects without the need for physical hardware, making it an accessible and cost-effective solution. However, while Wokwi and similar platforms offer valuable learning opportunities, they lack the immersive experience provided by VR. This limitation highlights the need for more advanced tools, such as VR-based platforms, to enhance IoT education.

VR and IoT integration

The integration of VR and IoT has the potential to revolutionize education by providing immersive, interactive learning experiences that closely mimic real-world scenarios. According to Hu *et al.* (2021), VR can enhance the user experience in IoT applications by providing multidimensional displays that allow users to interact with virtual devices in real time. For example, VR can simulate smart home environments in which students can configure IoT devices such as smart lights, thermostats, and security systems. This hands-on experience is crucial for developing practical skills and understanding the complexities of IoT systems. Furthermore, Alfaisal *et al.* (2022) argued that VR can improve the scalability of

IoT education by allowing multiple students to interact simultaneously with the same virtual environment. This collaborative approach not only enhances learning outcomes but also fosters teamwork and communication skills, which are essential for success in the IoT industry. By integrating VR with IoT education, institutions can provide students with a comprehensive learning experience that combines theoretical knowledge with practical skills.

Challenges in VR-based IoT education

Despite the potential benefits of VR in IoT education, several challenges must be addressed to ensure its successful implementation. Radianti *et al.* (2020) identified cost as a significant barrier, as VR equipment can be expensive, particularly for resource-constrained educational institutions. In addition, the development of high-quality VR content requires specialized skills and resources, which may not be readily available in all institutions. Another challenge is the potential for simulation sickness, which can occur when users experience discomfort or nausea while using VR headsets. Rebenitsch and Owen (2016) suggested that this condition can be mitigated through the careful design of VR environments, including the optimization of frame rates and the reduction of latency. However, this requires additional resources and expertise, which may further increase the cost of VR-based education. Finally, Makransky *et al.* (2019) highlighted the importance of aligning VR content with learning objectives to ensure that students achieve the desired outcomes. This requires close collaboration between educators and VR developers to create content that is both engaging and educationally valuable. Despite the challenges, the potential benefits of VR in IoT education make it a promising tool for enhancing learning outcomes and preparing students for future careers in the field.

Theoretical framework

This study is grounded in constructivist learning theory and experiential learning. VR supports constructivism by allowing learners to build knowledge through active exploration rather than passive reception. By enabling students to "pick, grab, connect, and assemble" components, VRIOTS facilitates the concrete experience and active experimentation stages of Kolb's learning cycle, thereby addressing the gap identified in traditional theoretical instruction (Abdulwahed & Nagy, 2009). Consequently, these theoretical frameworks dictated specific design choices within VRIOTS. Guided by constructivist principles, the platform prioritizes open-ended interactive tasks over static tutorials, compelling students to actively construct their technical knowledge (Huang *et al.*, 2010). Additionally, to facilitate the "Reflective Observation" phase of Kolb's cycle, the system incorporates immediate diagnostic feedback; when a student misconfigures a network node, the system visualizes the error instantly, prompting critical analysis and self-correction (Dalgarno & Lee, 2009). Finally, realistic industrial scenarios were engineered to ground these abstract concepts in authentic vocational contexts, ensuring skills are transferable to actual job roles.

METHODOLOGY

Agile methodology

The development of VRIOTS followed the Agile methodology, an overarching framework which is widely adopted in software development that emphasizes iterative progress, collaboration, and flexibility. Agile is particularly suited for projects such as VRIOTS, in which requirements may evolve over time and continuous feedback is essential for refining the product. Agile encompasses specific methodologies, such as Scrum and Kanban, which focus on delivering small, incremental improvements rather than a final product at the end of the development cycle (Beck *et al.*, 2001). This approach allows for rapid adaptation to changes and ensures that the final product meets users' needs. Figure 1 shows the phases of the Agile methodology.

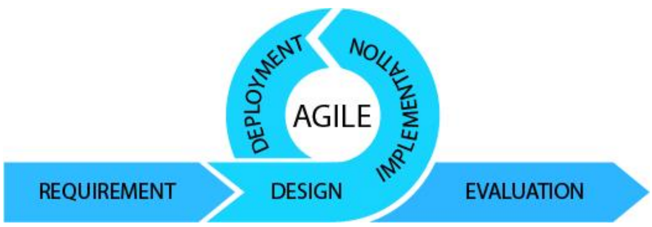

Figure 1. Agile methodology model.

In the context of VRIOTS, the Agile Virtual Reality System (VRS) was chosen because it is specifically designed for a VR-based system and aligns with the project's goals of creating a user-centric VR platform. The iterative nature of Agile VRS allowed the development team to incorporate feedback from educators and students at every stage of the project, ensuring that the platform was both educationally valuable and user-friendly. In addition, Agile's emphasis on collaboration fostered a cohesive team environment in which developers, designers, and educators worked together to address challenges and refine the platform.

Phases of Agile development

The Agile development process for VRIOTS was divided into five key phases: Requirement analysis, design, implementation, deployment, and evaluation. Each phase involved iterative cycles of development, testing, and feedback, ensuring that the platform evolved in response to user needs. The chosen methodology is illustrated in Figure 2, which outlines the actions taken in each phase of the process. This ensured that the project progressed in the necessary direction to achieve its objectives and deliver the expected results.

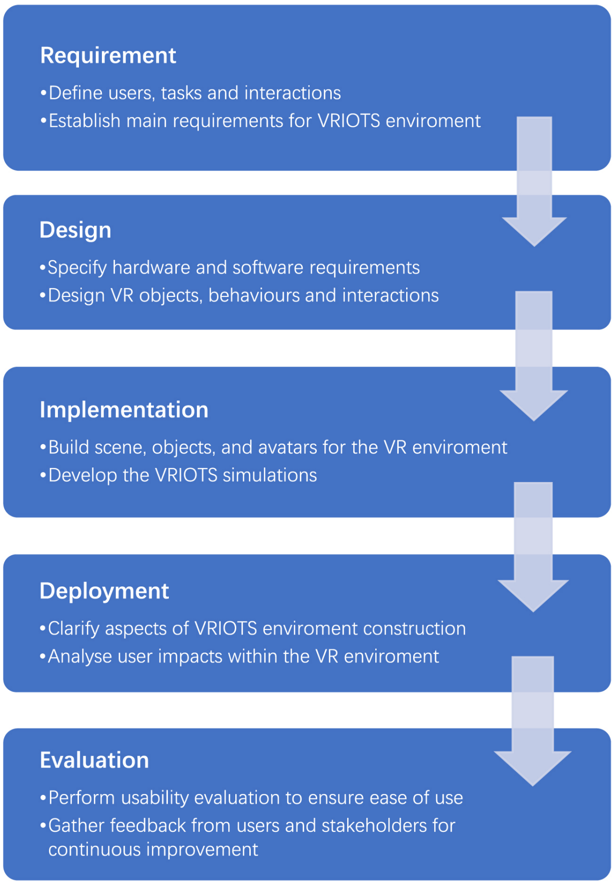

Figure 2. Phases of the Agile VR System methodology. VR, virtual reality.

Requirement analysis

The first phase involved identifying the target users and defining the functional and nonfunctional requirements of the VR environment. Functional requirements included features such as realistic IoT device simulation, interactive tutorials, and level-based project templates. Nonfunctional requirements focused on scalability, compatibility with VR hardware, and usability standards. This phase also involved conducting surveys and interviews with potential users to gather insights into their needs and expectations.

Design

The design phase focused on creating virtual IoT devices and user interactions within the VR environment. The platform was designed to include level-based IoT projects, with each level increasing in complexity. Users could interact with virtual devices using VR controllers or keyboard and mouse inputs, depending on the hardware available. The design phase also involved creating wireframes and prototypes, which were tested with a small group of users to gather feedback on usability and functionality. Figure 3 shows a design diagram for an IoT device using the ESP32 (Espressif Systems, Shanghai, China) board simulated in VRIOTS.

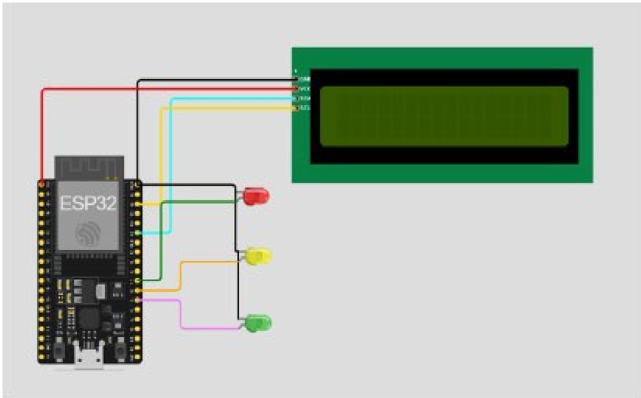

Figure 3. Design diagram for IoT devices. IoT, Internet of Things.

To demonstrate the platform's pedagogical approach, we detail a typical learning task: Visualizing Connectivity with Output Modules. In this session, the student operates within the immersive three-dimensional (3D) workspace to connect three main components an ESP32 controller, a light emitting diode (LED) light, and an LED status screen to build a system that visually indicates a successful connection.

The student follows a step-by-step workflow designed to mirror real-world IoT prototyping, assisted by intelligent virtual guidance. The student enters the immersive virtual lab and selects the required hardware: An ESP32 microcontroller, a standard LED, and an LED display module (Figure 4). Using the VR controllers, they pick up and manipulate these 3D objects, rotating them to inspect pinouts before arranging them on the virtual breadboard, replicating the spatial planning required in a physical lab. Students use virtual connector wires to link the components. To provide immediate guidance, the system utilizes a snap-to-fit interaction mechanic (Figure 5). As the student brings a cable connector close to a pin, the wire will automatically "snap" into place only if the connection point is valid (*e.g.*, connecting a cable to a valid header). If the student attempts an incorrect connection (such as connecting to a non-conductive surface or a physically incompatible port), the wire will not snap. This mechanism acts as a virtual scaffolding tool, preventing fundamental physical errors while training the student to recognize correct port alignment and pin positioning. Finally, the student powers the simulation. They verify success by observing two physical indicators within the 3D environment: The LED lighting up and the status text rendering on the virtual LED screen (Figure 5). This replicates the standard industry practice of using visual hardware indicators to debug IoT devices in the field.

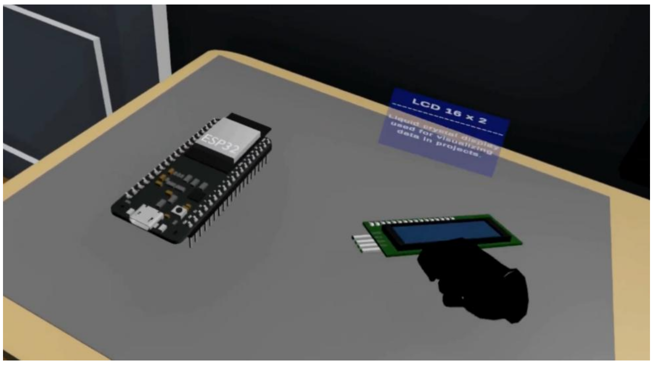

Figure 4. Grabbing virtual components.

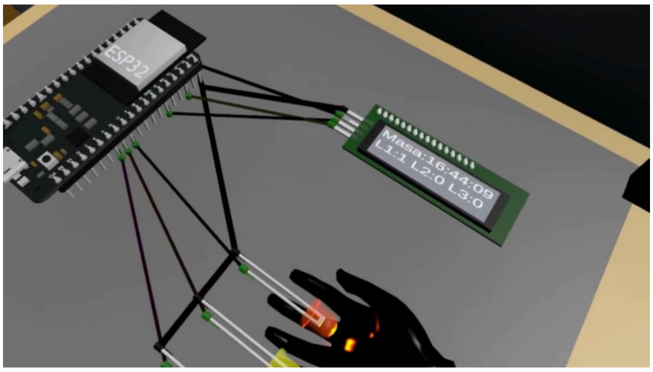

Figure 5. Snap-to-fit interactions.

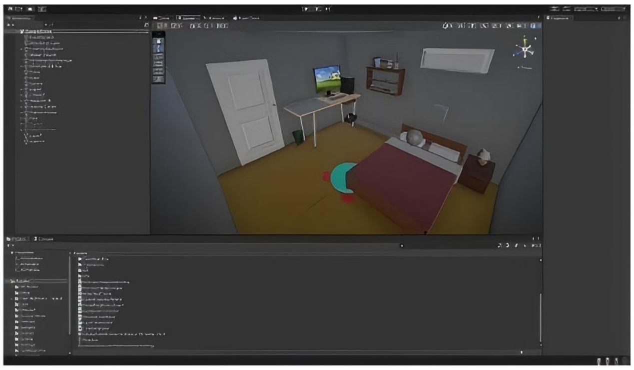

Figure 6. Unity 3D integrated development environment.

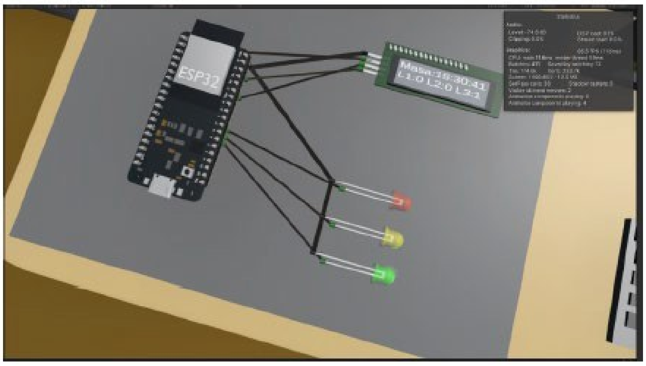

Figure 7. VRIOT assembly simulation.

Implementation

During the implementation phase, the VR environment was developed using tools such as Unity 3D and Blender. The platform included 3D virtual environments, interactive IoT devices, and guided tutorials to provide a hands-on learning experience. The implementation also involved building scenes, objects, and coding for features such as connecting components and ensuring proper connections between devices. Figure 6 shows the Integrated Development Environment (IDE) in Unity 3D and the design of the virtual environment in VRIOT simulations.

Deployment

The deployment phase involved finalizing the setup and configuration of the VR environment and ensuring that all hardware and software components were properly integrated. User testing was conducted to evaluate engagement levels, learning outcomes, and usability challenges. This phase also included creating user documentation and training materials to help educators and students navigate the platform. Figure 7 shows the actual environment designed in the VRIOTS virtual environment, in which the user can pick, grab, connect, and assemble IoT devices according to the instructions and information provided.

Evaluation

The evaluation phase included usability testing and the gathering of feedback from users and stakeholders. Early feedback indicated that the VR environment was effective in enhancing students' understanding of IoT concepts and providing an engaging learning experience. This phase also involved analyzing quantitative data, such as completion rates and user engagement metrics, to assess the platform's effectiveness.

Participants

This study employed a purposive sampling method involving 35 participants selected from Politeknik Balik Pulau, Pulau Pinang, Malaysia. The cohort consisted primarily of year 3 students enrolled in the Diploma in Digital Technology program. Additionally, educators from the Department of Information and Communication Technology (ICT) were included to evaluate pedagogical relevance. While the educators possessed advanced technical proficiency, the student participants entered the study with varying levels of prior IoT exposure, ranging from fundamental theoretical knowledge to limited practical application. It is important to note that the same group of participants were involved in the usability testing, the survey questionnaire, and the interview sessions. This ensured consistency between the quantitative performance metrics and the qualitative feedback. The participants consisted primarily of students and educators with varying levels of exposure to IoT technology, as shown in Table 1.

Table 1: Participant demographics

Metric	Category	Frequency (*n* = 35)	Percentage
Role	Students	30	85.7
	Educators	5	14.3
Gender	Male	20	57.1
	Female	15	42.9
Prior IoT experience	Basic	23	65.7
	Expert	12	34.3

IoT, Internet of Things.

Instruments

Four primary instruments were used. (1) A user satisfaction and engagement interview guide: This included qualitative questions focused on user experience, navigation challenges, and engagement (Table 2). (2) Focus group discussions: These included qualitative questions focused on usability, effectiveness, barriers, and improvements (Table 3). (3) A user satisfaction and engagement survey: This survey gathered data on satisfaction, navigation, and perceived effectiveness. The items were measured using a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree), as indicated by satisfaction ratings of 4-5 out of 5 in the results (Table 4). The instrument demonstrated strong internal consistency, with a calculated Cronbach's alpha of 0.87. (4) A usability testing log: This recorded objective metrics, including task completion rate, time on task, and error rate (Table 5).

Table 2: User satisfaction and engagement interview questions

Item	Question
1	How would you describe your experience using the VRIOTS platform?
2	Did you find the VR environment easy to navigate? If not, what challenges did you face?
3	How engaging were the interactive tutorials? Did they help you better understand IoT concepts?
4	What improvements would you suggest to make the platform more effective for learning?

VR, virtual reality; IoT, Internet of Things.

User feedback methodology

User feedback was a critical component of the Agile development process for VRIOTS. Feedback was gathered through a combination of qualitative and quantitative methods to ensure a comprehensive understanding of user experiences and needs.

Table 3: Focus group discussions

Item	Question
1	Discuss the overall usability of the VRIOTS platform
2	Share your thoughts on the effectiveness of the VR simulations in teaching IoT concepts
3	Identify any challenges or barriers you encountered while using the platform
4	Suggest potential features or improvements that could enhance the learning experience

VR, virtual reality; IoT, Internet of Things.

Table 4: User satisfaction and engagement questionnaire

Item	Question
1	How satisfied are you with the VRIOTS platform?
2	How easy was it to navigate the VR environment?
3	Did the platform improve your understanding of IoT concepts?
4	How likely are you to recommend VRIOTS to other students or educators?

VR, virtual reality; IoT, Internet of Things.

Table 5: Usability testing metrics

Item	Testing metric
1	Task completion rate: Percentage of users who successfully completed a given task (*e.g.*, configuring an IoT device)
2	Time on task: Average time taken by users to complete a task
3	Error rate: Number of errors made by users while performing a task
4	User engagement: Time spent interacting with the VR environment

VR, virtual reality; IoT, Internet of Things.

Qualitative feedback

Qualitative feedback was collected through user interviews (Table 2) and focus group discussions (Table 3). These methods allowed the development team to gain in-depth insights into user experiences, preferences, engagement, and challenges as well as the overall usability of VRIOTS. For example, students were asked about their experience with the VR environment, including how easy it was to navigate, how engaging the tutorials were, and whether they felt that the platform improved their understanding of IoT concepts. Educators provided feedback on the platform's educational value, including its alignment with curriculum objectives and its potential for use in classroom settings.

Quantitative feedback

Quantitative feedback was gathered through surveys and usability testing. Surveys were distributed to a larger group of users to gather data on user satisfaction, ease of use, and perceived effectiveness of the platform (Table 4). Usability testing involved observing users as they interacted with the VR environment and tracking metrics such as task completion rates, time spent on tasks, and error rates (Table 5). These data were used to identify areas for improvement and to validate the platform's effectiveness in achieving its learning objectives.

Data analysis

Qualitative analysis

Feedback from interviews and focus groups was analyzed using thematic analysis. Responses were coded to identify recurring patterns regarding usability challenges, learning value, and engagement.

Quantitative analysis

Survey data and usability metrics were analyzed using descriptive statistics (mean scores and percentages). Given the pilot nature of this study (n = 35) and the absence of a control group, inferential statistics (t-tests) were not applied in this phase. The analysis focused on establishing baseline feasibility and user satisfaction levels.

Usability metrics analysis

Objective data logged by the system were analyzed to determine efficiency and error frequency.

RESULTS AND DISCUSSION

The VRIOTS platform was evaluated through surveys, interviews, focus groups, and usability testing with 35 participants to assess its effectiveness in teaching IoT concepts through VR. The results revealed high engagement and learning potential, although some usability challenges were identified. In this section, the findings are organized according to the study's RQs, integrating both quantitative descriptive statistics and qualitative thematic analysis to provide a comprehensive evaluation of the VRIOTS platform.

Design validity and operational realism

RQ1: How can an immersive VR environment be designed to accurately simulate IoT device configuration and interaction?

Analysis method: Qualitative thematic analysis

To answer RQ1, participant feedback was analyzed from interviews to determine whether the virtual environment successfully mimicked the logic and physical constraints of real-world IoT hardware.

Findings

The thematic analysis identified a dominant theme: Operational realism and safety. The participants consistently noted that the platform allowed them to visualize circuit connections that are often abstract in 2D diagrams.

Visualizing connections

The schematic designs (Figure 6) were successfully translated into 3D interactive objects. Participants confirmed that being able to walk around the table (3D environment) and inspect the ESP32 microcontroller from different angles aided their spatial understanding.

Safe experimentation

A key subtheme was the risk-free environment. As noted by one participant: "It was great to experiment without worrying about burning out a sensor. I felt like I could try things I wouldn't do with the expensive physical kits."

These findings confirm that the design successfully translated the functional requirements into a usable simulation, satisfying RQ1 by providing a realistic, risk-free alternative to physical hardware.

Learning effectiveness and engagement

RQ2: To what extent does the VRIOTS platform support student engagement and perceived understanding of IoT concepts?

Analysis method: Quantitative descriptive statistics

To answer RQ2, the usability testing metrics (Table 6) and a comprehensive analysis of subjective evaluation items, both quantitative and qualitative, were used, integrating the descriptive statistics from the survey (Likert Scale 1-5) with the thematic findings from the interview/focus groups (Table 7).

Findings: Engagement and task success

The objective performance data presented in Table 6 offer critical insights into the functional viability of the VRIOTS platform as a learning tool.

High task feasibility and scaffolding

The task completion rate of 85.7% (30 out of 35 participants) is a significant indicator of the platform's effectiveness. This high success rate suggests that the virtual environment successfully scaffolds the complex process of IoT circuit assembly. By stripping away the physical risks (*e.g.*, short-circuiting expensive boards) and providing visual cues, VRIOTS enables the majority of students—including those with limited prior experience—to achieve the learning objective.

Consistency and efficiency

The average time on task (3.20 min), combined with a relatively low standard deviation (0.82 min), indicates a consistent workflow across the participant group. This suggests that once users overcome the initial learning curve of the VR controls, the actual process of configuring the virtual IoT device is efficient. This efficiency is crucial for vocational education, as it allows for

Table 6: Usability testing metrics results

Metric	Measurement unit	Mean/frequency	SD	Analysis
Task completion rate	% of success	85.7% (30/35 participants)	N/A	The high completion rate indicates that the platform effectively scaffolds the assembly process.
Time on task	Minutes	3.20 min	0.82 min	The low standard deviation suggests consistent workflow across the participant group.
Error rate	Errors per task (mostly UI-related)	1.50 errors	0.60 errors	The errors were primarily non-critical UI interactions (*e.g.*, dropping components) rather than logic failures.
User engagement	Minutes	12.50 min	2.10 min	This indicates sustained engagement and attention throughout the learning module.

SD, standard deviation; UI, user interface.

Table 7: Qualitative and quantitative analysis results

Evaluation category	Quantitative survey item (*n* = 35)	Quantitative results (Mean ± SD), satisfaction rate (%)	Qualitative interview item	Key qualitative finding/theme
User experience and satisfaction	Q1. How satisfied are you with the VRIOTS platform	3.85 ± 0.95, 68.6%	Q1. How would you describe your experience using the VRIOTS platform?	Theme: Immersion *vs.* comfort Participants praised the immersive environment but noted physical discomfort (dizziness) during extended use
Navigation and usability	Q2. How easy was it to navigate the VR environment	3.10 ± 1.20, 51.4%	Q2. Did you find the VR environment easy to navigate? If not, what challenges did you face?	Theme: Fine motor control challenges Users struggled with grabbing small wires using controllers. This explains the lower quantitative score and the 1.5 error rate
Learning value	Q3. Did the platform improve your understanding of IoT concepts	4.25 ± 0.75, 82.9%	Q3. How engaging were the interactive tutorials? Did they help you better understand IoT concepts?	Theme: Visualizing connections 3D visualization helped students see logical connections (*e.g.*, pins to sensors) that are abstract in 2D diagrams
Future adoption	Q4. How likely are you to recommend VRIOTS to other students or educators?	3.90 ± 0.85, 71.4%	Q4. What improvements would you suggest to make the platform more effective for learning?	Theme: Accessibility and onboarding Students recommended adding a "desktop mode" for those with motion sickness and "better onboarding" tutorials for VR novices

SD, standard deviation; 3D, three-dimensional; VR, virtual reality; IoT, Internet of Things.

repeatable experiments within a standard class period—something often limited in physical labs due to setup and teardown time.

Interpreting the error rate

The recorded error rate of 1.50 errors per task requires careful interpretation. When triangulated with qualitative feedback on navigation difficulties, it becomes evident that these errors were predominantly interaction based (*e.g.*, failing to grab a wire or dropping a sensor) rather than cognitive (*e.g.*, wiring a pin to the wrong port). This distinction is vital: Students understood the IoT concepts but struggled with the VR interface. This finding highlights a specific area for future development: The need for snap-to-grid or assisted manipulation features to lower the motor-skill requirements of the simulation.

Sustained engagement

Finally, the average session duration of 12.50 min reflects sustained engagement. In a traditional theoretical setting, maintaining active attention on circuit diagrams for this duration can be challenging. The immersive nature of VR, which creates a sense of presence, appears to hold student attention effectively, allowing for a deeper "learning by doing" experience that aligns with the study's constructivist framework.

As shown in Table 7, there was convergence between the datasets.

High learning value

The highest quantitative score (Mean = 4.25) aligns with the qualitative feedback regarding visualizing connections. This confirms that while the interface had challenges, the educational content was highly effective.

Navigation issues

The lowest quantitative score (Mean = 3.10) can be directly explained by the qualitative theme of fine motor control challenges. Triangulation revealed that the error rate (Table 6) was driven by UI friction rather than by a lack of conceptual understanding.

Satisfaction vs. Frustration

The overall satisfaction (Q1) score of 68.6% (Mean = 3.85) reflects a balance between these two opposing forces. While students appreciated the immersive learning and "risk-free" environment, their enthusiasm was tempered by the physical friction of using the controllers. However, the high likelihood of recommending (Q4; Mean = 3.90; 71.4%) indicates that participants viewed these navigation issues as "growing pains" rather than fatal flaws, recognizing the potential value of the tool for their peers.

Implications for design

The disparity between Q3 (learning) and Q2 (navigation) serves as a clear directive for future development; that is, the simulation logic is sound, but the user interface must be refined. Improving the onboarding process and adding accessibility features, such as "snap-to-grid" wiring, could close this gap, potentially raising overall satisfaction to match the high learning outcomes.

Discussion of RQ2

The results indicate a strongly positive answer to RQ2. The 85.7% task completion rate acts as a proxy for procedural learning, showing that students could successfully apply IoT logic. Furthermore, an improved understanding score of 82.9% suggests that the immersive nature of VR (sense of presence) contributed to their confidence in the subject matter, aligning with constructivist learning theories.

Challenges and user experience

RQ3: What usability challenges and user experiences are associated with implementing VR in a technical curriculum?

Analysis method: Mixed-method triangulation

To answer RQ3, the quantitative error rates were cross-referenced with qualitative codes regarding navigation and comfort.

Quantitative findings: Usability friction

While engagement was high, usability scores highlighted specific friction points. (1) Error rate: The system recorded an average of 1.50 errors per task. (2) Navigation score: As shown in Table 7, navigation and usability received the lowest satisfaction score (51.4%, Mean = 3.10).

Qualitative findings: Navigation

The thematic analysis explained why the navigation score was low, with ergonomic challenges a recurring theme. (1) Motion sickness: Consistent with Rebenitsch and Owen (2016), several participants reported mild dizziness or "simulation sickness", particularly during rapid movement within the virtual room. (2) Fine motor control: Users noted difficulty manipulating small components (*e.g.*, wires) using VR controllers. One participant remarked: "I understood the concept, but moving around the room and grabbing the small wires was frustrating at first."

Together, these findings suggest that while the VR environment successfully facilitates procedural learning and boosts student confidence, its pedagogical effectiveness is currently tempered by ergonomic friction. The distinct contrast between high task completion rates and lower navigation satisfaction indicates that the primary barrier for students is not the complexity of the IoT subject matter, but rather the mechanical demands of the VR interface itself. Specifically, the challenges regarding fine motor manipulation and simulation sickness highlight that while the cognitive scaffolding is effective, the physical interaction mechanics require refinement to minimize extraneous cognitive load and ensure a seamless user experience.

Discussion of RQ3

Triangulating the 1.5 error rate with the interview data confirms that the errors were predominantly UI-related rather than conceptual. The challenge in implementing VR for IoT is not the complexity of the subject matter but the accessibility of the interface. Although VRIOTS succeeds as a logic simulator, the physical interaction layer requires refinement (*e.g.*, better "snap-to-grid" features) to reduce cognitive load and motion sickness.

In the broader context of TVET, these findings suggest VRIOTS can serve as a crucial bridge between theoretical instruction and industrial application. The platform functions effectively as a pre-lab training ground, allowing beginners to rehearse complex cabling and configuration tasks safely before engaging with physical hardware, thereby minimizing equipment damage and material waste. Furthermore, by simulating authentic industry workflows such as end-to-end IoT deployment, ensuring access to specialized learning beyond the physical classroom. This alignment with real-world operational standards directly supports school-work transitions, enhancing students' work readiness and employability for emerging roles in the IoT sector.

Advantages of VRIOTS

The platform enhances learning by providing students with hands-on practical experience, allowing them to actively engage in IoT projects, while its interactive gameplay increases engagement and makes learning more enjoyable, thereby boosting student motivation. In addition, by utilizing virtual hardware models, the platform offers a cost-effective solution that reduces the need for expensive physical equipment, making IoT education more accessible to a wider audience.

Limitations

Although the VR environment delivers a realistic simulation of IoT systems, it may not perfectly replicate all nuances of physical hardware interactions, which could limit certain hands-on learning experiences.

CONCLUSION AND RECOMMENDATIONS

Conclusion

This study demonstrates that VRIOTS is a viable complementary tool for TVET education. While VRIOTS offers a cost-effective solution to the hardware access problem thus addressing the study's background problem the usability findings suggest that a hybrid approach is best. VRIOTS should be used as a pre-lab experience in which students learn the logic and safety protocols (high task completion, high perceived learning) before moving to physical labs, thereby minimizing the impact of VR-specific navigation challenges.

The VRIOTS project showcases the transformative potential of VR in IoT education, offering an immersive, interactive, and cost-effective learning solution. By leveraging realistic virtual simulations, the platform bridges the gap between theoretical knowledge and hands-on experience, allowing students to design, build, and troubleshoot IoT systems in a risk-free, scalable environment. This innovative approach enhances comprehension by enabling learners to visualize complex IoT concepts in 3D, while gamified elements boost engagement and motivation. Although the initial VR hardware costs may pose a challenge for some institutions, the long-term benefits such as reduced reliance on physical equipment, remote accessibility, and repeatable experiments make it a sustainable and scalable alternative to traditional labs. Moreover, by preparing students with practical skills in IoT development, the VRIOTS platform helps bridge the industry-academia gap, equipping the next generation of engineers and developers with the expertise needed for emerging smart technologies. While the simulations may not fully replicate every aspect of physical hardware interaction, the platform serves as a powerful complementary tool, enhancing IoT education in previously unattainable ways. Ultimately, VRIOTS represents a significant step forward in modernizing technical education, proving that VR-powered learning can be a game changer in building a skilled workforce for an IoT-driven future.

Recommendations

Continuous feedback and improvement: Regular feedback from users and stakeholders should be gathered to refine and enhance VR simulations over time. Gamification elements: Adding game-like elements such as challenges, rewards, and progression systems can further boost student engagement and motivation. Accessibility considerations: The platform should be designed to accommodate users with different needs, including adjustable text sizes, multi-language support, and compatibility with assistive technologies.

DECLARATIONS

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None.

Author contribution

Razif M: Supervison, Conceptualization, Methodology, Software, Writing—Original draft. Nazurah H: Writing—Review and Editing, Visualization. Asnidatul A: Formal analysis, Data Analysis, Literature Review. All authors have read and approved the final version.

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Ethical approval

Not required.

Informed consent

The participants were informed that the interview data were only used for research purposes, and their information would be anonymized when presenting the research result. Moreover, they are also allowed to stop the recording at any moment during the interview, and they can refuse to respond to any question asked during the review.

Conflict of interest

The authors have no conflicts of interest to declare.

Use of large language models, AI and machine learning tools

During the preparation of this work the authors used Gemini Pro in order to literature collection and language polishing. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Data availability statement

Data used to support the findings of this study are available from the corresponding author upon request.

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