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Work-in-Progress – Design and Development of an Immersive Virtual Reality Laboratory for Electrical Circuits

Rimneet Cheema[1], Kaden Watt[1] and Hossain Samar Qorbani[1]
[1]MacEwan University, Edmonton, Canada
cheemar9@mymacewan.ca, wattk23@mymacewan.ca,
samarqorbanih@macewan.ca

Abstract. Learning electrical circuits has been challenging for students over various education levels due to the abstract and non-observable nature of electrical phenomena. Immersive virtual reality (VR) offers new opportunities to support circuit exploration through embodied interactions and real-time visualization. This work-in-progress paper presents the development and evaluation of an educational immersive VR laboratory for electrical circuit simulation that allows users to construct and manipulate series and parallel circuits using natural hand-based interactions. Developed in Unity and deployed on a Meta Quest headset using hand tracking, the laboratory was designed to support experiential learning through active exploration and real-time feedback. A small-scale user study with seven participants from a university computer science and virtual reality course evaluated usability, immersion, and comfort through observation and standardized questionnaires. The results show that the system was intuitive and engaging and supported a strong sense of presence, demonstrating the feasibility of immersive VR laboratories as a complementary tool for circuit education.

Keywords: Virtual Reality, Education, Physics, Circuitry.

1 Introduction

Physics education often relies on the use of visual representations to support the understanding of abstract concepts, particularly in topics such as electrical circuits where system behavior and interactions are not directly observable by the learner [1, 3]. The exploration of virtual reality or VR as an educational tool has increasingly become an area of interest due to its ability to provide immersive environments that can support interaction, exploration, and repeated experimental learning [2, 11]. Additionally, within science education, researchers often investigate VR as a tool for virtual laboratory environments that can support interactive experimentation and real-time visualization of non-observable phenomena [2, 3].

This research aims to develop and evaluate an educational VR laboratory for electrical circuit simulation in a higher education context. The developed VR Laboratory is focused on the exploration of fundamental circuit principles including series and parallel circuits through the interactive manipulation of components such as batteries, resistors, and light bulbs. Designed to support experiential learning through active exploration and real-time feedback, the laboratory was developed for students exploring introductory circuit concepts. A small-scale user study was conducted with participants from a university computer science and virtual reality course to evaluate usability, immersion, and comfort.

2 Related Works

Research in physics education has found that students across various educational levels experience challenges and misconceptions when it comes to electrical concepts such as current flow, resistance, and circuit behavior [4, 6]. These misconceptions are often correlated to the abstract and non-observable nature of electrical phenomena, which can make it challenging for learners to develop accurate mental models using conventional instructional approaches alone [3]. In response to these challenges, educational researchers have explored virtual-based environments as a potential tool for supporting conceptual understanding by providing visual representations of otherwise invisible processes [3].

Building on this, a substantial amount of research has examined the use of computer-based Virtual Laboratories (VLs) in the context of electrical circuit education, particularly through comparison with Physical Laboratories (PLs). Prior studies have reported that VLs can effectively support conceptual learning of circuit theory and in some cases produce learning outcomes exceeding those in PL settings [4, 5]. Tekbiyik and Ercan found that students in the VL group achieved higher conceptual understanding scores than those working exclusively in the PL [4]. More recent work by Papalazarou et al. reported not only comparable learning outcomes between PLs and VLs, but showed VLs yielding higher levels of student interest and engagement [5]. On the contrary, Tokatlidis et al. noted that although both approaches improved conceptual knowledge, PLs remained more effective for developing measurement and instrument handling skills [6]. However, rather than positioning VLs as replacements for PLs, subsequent research highlights complementary strengths rather than interchangeable solutions [7]. Hybrid approaches combining both PLs and VLs have also been shown to be beneficial; Jaakkola and Nurmi reported that students who engaged in hybrid experimentation outperformed those using a single laboratory format [7].

While these studies provide valuable insight into computer-based VLs, they do not address the unique capabilities of immersive VR environments, such as 3D interaction, embodied control, and real-time visualization [2, 10]. More recent research has therefore shifted toward immersive Virtual Reality Laboratories (VRLs), which can extend beyond standard VLs by enabling embodied interaction and spatial visualization [2, 10]. In the context of electrical circuits, Bazangike et al. emphasized the importance of instructional design and curriculum alignment when evaluating virtual physics laboratories [8]. Similarly, Wolbach demonstrated that VR circuit simulations with advanced visualization techniques allow students to directly observe invisible electrical circuit processes such as current flow and voltage distribution in real-time, and have shown to enhance comprehension of circuit behaviour [9].

Beyond electrical circuit applications, VRLs have been increasingly explored across not just physics but broader STEM education. Systematic reviews of immersive VR in STEM education indicate that immersive technologies support user experience, engagement, and visualization of complex and non-observable concepts in higher education settings [10].

Overall, the existing literature indicates that immersive VRLs may retain the conceptual and engagement-related benefits observed in the earlier VLs while also introducing new opportunities for embodied interactions, spatial exploration, and real-time feedback that are difficult to achieve in physical or desktop-based settings. Taken together, this literature suggests the relevance of investigating immersive VR laboratories for electrical circuits, not only as a technical simulation approach, but also as a potentially useful instructional tool that can complement existing laboratory formats.

3 Methodology and Testing

3.1 Development

The VR Circuit Simulation was developed to provide an immersive, hands-on learning environment aligned with fundamental circuit theory. The system was built using the Unity game engine, which provided scene management, real-time rendering, physics simulation, and interaction handling. A long-term support version of Unity was used to ensure stability and compatibility with contemporary XR development tools. The simulation was deployed on the Meta Quest headset, chosen for its reliable hand-tracking capabilities and accessibility in educational settings. Hand tracking was implemented using XR Hands and the XR Interaction Toolkit, allowing users to reach, grasp, place, and release components such as batteries, resistors, and light bulbs. Natural hand interactions were intended to reduce cognitive interface complexity, enabling learners to focus more directly on circuit behavior.

The virtual environment was designed to resemble a spaceship lab, with interaction tables, storage areas for components, and a display for real-time electrical calculations. The VR laboratory was intended to support the exploration of introductory circuit concepts by allowing learners to assemble series and parallel circuits, observes changes in current, voltage and resistance, and compare circuit behaviour through immediate visual feedback. Fig. 1 shows the VR laboratory environment developed for series and parallel circuit exploration. Assets were created in Blender, scaled for intuitive manipulation, and integrated into Unity with environmental effects including lighting and ambient sound to increase immersion. Circuit simulation logic was implemented using an event-driven architecture linked to XR Interaction Toolkit sockets. Components snapped into place through socket constraints, triggering immediate circuit recalculation. Electrical behavior was modeled using Ohm's Law, with voltage defined by battery inputs and resistance values assigned to individual components. Series and parallel circuits were managed separately. In series circuits, current only flows when all component slots are filled, while in parallel circuits each branch operates independently. Bulb brightness and displayed numerical values for voltage, current, and resistance provide real-time visual feedback.

This design was intended to balance conceptual accuracy with user interaction, supporting exploration of circuit principles while maintaining immersive and intuitive controls. The combination of natural hand interactions, interactive component manipulation, and real-time feedback provides a platform for experiential learning, allow-ing users to visualize otherwise invisible electrical processes while supporting exploration of series and parallel circuits.

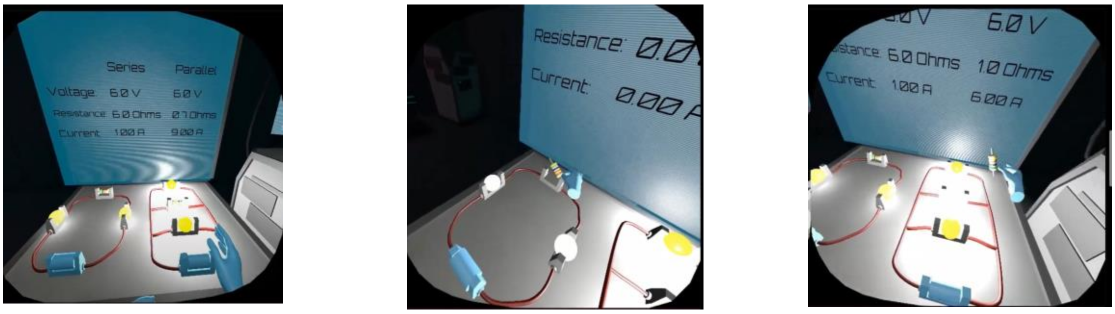


Fig. 1. VR Laboratory Workstation for Series and Parallel Circuits.

3.2 Participants

For this study, we enlisted seven participants from the CMPT 499 course, a computer science and virtual reality class, at Grant MacEwan University. All participants had some familiarity with virtual environments and prior exposure to VR technology. Participation was voluntary, and all participants were informed about the purpose of the study and the tasks they would perform. While they had no prior experience with the VR Circuit Simulation, they were aware of its existence and may have seen pictures of it beforehand. Both rounds of testing involved the same pool of participants, allowing for consistency in evaluating changes between the two rounds.

3.3 Procedure

The study was conducted in two rounds, each employing different approaches to evaluate usability, engagement, and overall user experience with the VR laboratory simulation. In the first round, the VR laboratory was in an initial stage of development, and participants interacted with placeholder circuit components to evaluate the feel of hand tracking, object placement, and the user interface. This round was primarily used to gather feedback on interaction feel, setup, and user interface design rather than on a fully functional circuit simulation. After implementing improvements based on this feedback, the second round of testing was conducted. In the second round, participants explored the VR laboratory simulation, with fully functional series and parallel circuits, and completed a structured survey to provide quantifiable feedback on their experience.

3.4 Data Collection

Data for the study were collected using both qualitative and quantitative methods. In the first round, feedback was gathered informally through direct observation and follow-up interviews. Detailed notes captured participants' experiences, highlighting both positive aspects and areas of difficulty. This qualitative data informed refinements to the VR Circuit Simulation before the second round. In the second round, quantitative data were collected through a survey using a Likert scale ranging from one (Strongly Disagree) to five (Strongly Agree). The survey included items adapted from the System Usability Scale (SUS), Igroup Presence Questionnaire (IPQ), and Simulator Sickness Questionnaire (SSQ), along with a section for general feedback where participants could provide additional observations. This combination of qualitative and quantitative data allowed for a comprehensive assessment of usability, engagement, and user experience in the VR simulation.

4 Results

4.1 Usability

Survey responses indicated a generally positive assessment of system usability. Survey responses suggested that participants found the circuitry intuitive and the natural hand interactions with components straightforward. As shown in Fig. 2(a), usability results were highly positive for recommending the VR Circuits Lab to other students, indicating strong overall usability and user satisfaction. Table 1 summarizes the responses to Question 1, ”What aspect of the Circuit Simulation did you find most engaging or educational?” Several participants highlighted that interacting with the components, particularly the light bulbs and batteries were a key engaging feature. This suggests that engagement was mainly tied to direct interaction with components and immediate visual system response. The visual feedback such as the changes in the light bulb colour, was frequently mentioned and perceived as helpful in understanding circuit behaviour. It is important to note that during this phase of user testing, the prototype had not implemented illumination of the light bulbs yet, at this point only the colours of the bulbs changed. Lastly, responses related to hand controls and object interactions suggested that most participants found them natural and intuitive. However, some participants reported minor usability challenges, particularly with the pop-up menu. As well as, a small number of users noted difficulty when placing components at further away locations in the circuit.

Table 1. Participant responses to the open-ended questions on engagement and discomfort.

Response	Question 1	Question 2
1	The interaction with the light bulbs and battery	No
2	Watching the light bulbs color change	No.
3	Hand controls	no
4	The way each circuit you build has information that is Not at all! accurate about it.	Not at
5	Seeing how the light interacted with varying resistance	Only when I had to reset my position
6	The ability to pick up and place the parts on the circuits was	None really nice and smooth to handle.

4.2 Sense of Presence and Immersion

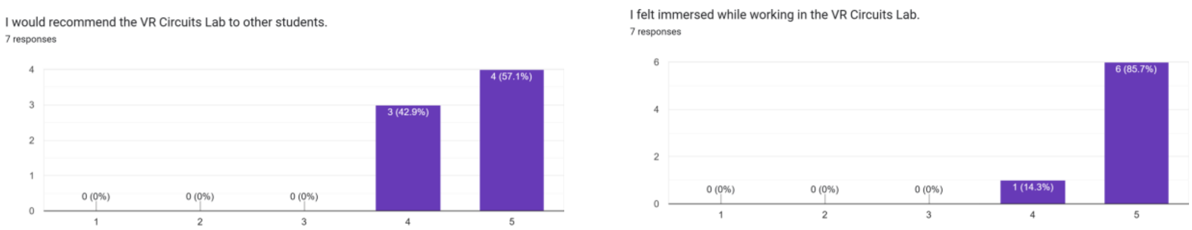
Survey results regarding the sense of presence indicated that participants generally felt strongly immersed in the environment. As shown in Fig. 2(b), responses were overall positive for immersion-related items, although some responses generated a need for improvement for the realism of the scene.

4.3 Simulator Sickness and Comfort

Table 1 also summarizes responses to Question 2, ”Were there any moments when you felt uncomfortable, disoriented, or sick?” Most responses were largely negative for discomfort and sickness, with only one participant reporting minor discomfort when resetting position. The overall responses suggested that the VR experience was comfortable and usable for the majority of users.

4.4 Overall Findings

These observations align with previous studies demonstrating the benefits of virtual and hybrid laboratory environments. As shown in Fig. 2, the survey responses overall reflected positive usability and immersion trends, while also identifying areas for refinement such as scene realism and interface interaction. The results suggest that the current VR simulation is feasible as an interactive laboratory prototype, with strengths in engagement, usability, and comfort. Future studies could expand on these findings by increasing sample size, including more diverse participants, and conducting direct comparisons with conventional laboratories to further evaluate learning outcomes.



(a) Usability Results. **(b)** Immersion Results.

Fig. 2. Survey Results.

5 Discussion and Conclusion

From a conceptual standpoint, the real-time visual feedback provided by the simulation, such as light bulb brightness and live numerical values for voltage, current, and resistance, appeared to support users in interpreting circuit behavior. This is reflected in the participant feedback, where several responses specifically mentioned the light bulb colour changes as engaging and found that the visual feedback made changes in the circuit easier to observe. The real-time responses appeared to support cause-and-effect reasoning.

Beyond visual feedback, the active manipulation of components allowed users to quickly test changes in the circuit. The immediate response of the system to component placement and removal suggests that the VR laboratory has potential to support exploration of concepts such as current, continuity in series circuits, and independent branch behavior of parallel circuits.

These findings align with prior research showing that virtual and immersive laboratories can help visualize non-observable phenomena. In pedagogical practice, this suggests that the VR laboratory may be useful as a complementary tool for guided circuit exploration alongside physical laboratories. Overall, this project presented the design, development, and initial evaluation of an immersive VR laboratory for visualizing electrical circuits. The system was designed to support active exploration of introductory circuit concepts through natural hand-based interaction and real-time feedback. Results from the small-scale user study suggest that the prototype was usable, engaging, and comfortable for participants, supporting its feasibility as a complementary educational tool. However, this was an early-stage evaluation with a small and relatively homogeneous participant group, and most participants has prior VR experience. In addition, the study did not directly measure learning outcomes. As such, the findings primarily demonstrate feasibility and user experience rather than confirmed learning gains. Future work should evaluate the system with larger and more diverse learner populations, particularly students studying introductory circuit concepts, while incorporating more formal learning assessments.

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