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BOARD #486: Development of Mixed Reality Labs in Circuits Theory

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Development of Mixed Reality Labs in Circuits Theory

Abstract—**As we enter Industry 4.0 and evaluate the reduction of location restriction in both business and learning, the potential for use of mixed reality (MR) modalities of engagement become apparent. Furthermore, educational institutions need the ability to adapt instruction by switching venues and modalities in light of pandemics, natural disasters, and even war to ensure effective teaching and learning are not compromised. This Work in Progress article discusses the development of MR instructional modules that address these purposes. We are developing mixed reality circuits labs to augment laboratory and classroom instruction of concepts critical to understanding electrical circuit theory and circuit implementation with the expectation of improving student outcomes in learning circuit theory and in building actual circuits. Four labs were developed to address deficiencies students deal with in learning circuits: 1) Bread-Board Basics and Series Circuits, 2) Parallel Circuits, 3) Series/Parallel Circuits, and 4) Superposition and Thevenin and Norton's Theorems. Prior to deployment, development of the MR lab software platform was necessary as was testing and troubleshooting. This article discusses the development process, critical paths and unanticipated challenges as well as student feedback from the first semester of use. These materials are presented in hopes of aiding others who seek to develop mixed reality applications for Engineering instruction.**

Keywords—formative assessment, active learning, retention, student-centered instruction

Introduction

The COVID-19 pandemic, in which traditional educational delivery was disrupted, highlighted the need for alternate, flexible and effective ways of educating students remotely. The instructors in the Electrical and Computer Engineering Department (ECE) at Prairie View A&M University noted the lack of in person processes and environments that were immersive and included social interaction compromised student learning outcomes. Observations made are as follows. Attendance and participation in Zoom class sessions were not consistent due to factors such as broadband access, illness, discouragement/burn-out, and distractions that drew students' attention away from online presentations. It was noted in general that students attending would "listen" to lectures, log in and have a digital presence, but could not demonstrate understanding of what was taught. Participation by those attending was also often problematic and following the pandemic, the social skills of a notable number of students had diminished.

Consideration of alternatives led researchers to discuss mixed reality as a way of implementing instruction that could involve virtual engagement with lab exercises and data gathering plus manipulation of digital representations. We teamed with the Chemical Engineering Department (CHEG) to complete the realization of digital assets in mixed reality as they had arrived at a similar goal during the pandemic.

Mixed Reality is an immersive experience in which students can interact with digital twins- digital representations of physical components that they would normally engage with in a lab or class setting- in addition to abstract concepts that have been made tangible through the flexibility that mixed reality affords. The digital elements are superimposed over the real environment in which users are working. The users are able to see and interact with each other plus the virtualized setting and the real world wearing a headset [1]. This is the type of environment that has the potential to address the concerns noted by the Electrical and Computer Engineering faculty and to enable social interaction, collaborative learning, manipulation of items and lab equipment, and completion of lab processes in a setting shared by a group of participants.

Mixed reality differs from virtual reality (VR) and augmented reality (AR). In virtual reality, the environment is completely or almost completely immersive. This would not be ideal for identified purposes because social interaction between the students would be limited [1]. Augmented reality is a superposition of the virtual environment onto the real environment with little to no interaction between the two. This differs from mixed reality in which there is interaction between the virtual environment and the real environment [2].

In addition,, a mixed reality setting provides the opportunity for social engagement and collaboration in both a local physical setting and the remote space thus capitalizing on social learning theory which notes that people can learn from interacting with others [3]. This pattern can address the diminished social skills observed as social learning affords several advantages: "Collaborative learning generates significantly higher achievement outcomes, higher-level reasoning, better retention, improved motivation, and better social skills than traditional didactics." [4-7]. Reference [4] in particular showed evidence of improved critical thinking and collaborative learning. Realizing the characteristics in the quote above is not only important for learning the content in the course but also as academic skills and outcomes that impact access to and success in professional life.

The advantages of using a mixed-reality format over a traditional physical lab are: 1. There is no maintenance associated with them; 2. Extra costs for equipment upgrades are not necessary, except for headset upgrades; 3. The virtual equipment does not require periodic calibrations as do real instruments. Notwithstanding, it is still important for students to have experience conducting real physical labs, as we don't live in a mixed reality world [17]. Having a digital twin of the physical lab serves the purpose of providing a lab experience that is available when physical labs are not and that can be performed in a dedicated location or remotely if conditions are not suitable to meet in person for a physical lab or for a mixed reality lab hosted in one physical place. The mixed reality lab can also be used to reinforce principles and skills learned in the physical lab environment and in the lecture. Furthermore, it allows students to collaborate together at one physical location or the option to collaborate remotely with each other as opposed to running an online simulation, which may not allow team interactions.

Given these findings from previous studies and knowledge of the learning needs of the student, the ECE and CHEG faculty were convinced that design and implementation of a mixed reality system platform for delivering instruction would be the most appropriate for supplementing instruction, especially when students and instructor are not meeting together in person.

It is also important to recognize that virtual reality is integral to the emergence of Industry 4.0, the fourth industrial revolution. Introducing our students to virtual reality/mixed reality now can give them a head start in preparing for this aspect of Industry 4.0.

Theoretical framework

A proposal was prepared and submitted to the National Science Foundation. The theoretical framework communicated included the observations of challenges for students in an exclusively digital environment made by the ECE faculty as well as educational theory and best-practice activities.

Theory regarding the nature and development of knowledge was one element of the theoretical background. Davenport and Prusak's definition of knowledge in [8], "a fluid mix of framed experience, values, contextual information and expert insights that provides a framework for evaluating and incorporating new experience and information" was employed with Tiwana's division of knowledge into explicit and tacit categories[8,9]. Explicit knowledge is conscious knowledge that is easily communicated, codified, stored and accessed. It is expressed in formal language, for example, through data, textbooks, scientific formulae, specifications, manuals, etc. Because it is inherently codifiable, a real benefit of this type of knowledge is that it has high fidelity and can be passed down through generations. Tacit or implicit knowledge is subconscious. By its very nature, this type of knowledge is difficult to express or extract and thus difficult to transfer to others because it is embedded in individual experiences. This type of knowledge is developed through a process of trial and error encountered only through personal practice and experience.

Framing of the project also involved the preferred learning patterns of 21st century students. The preference to be engaged in processes that are interactive, ubiquitous and regular use of digital technologies and content, an interest in being "heard" and contributing, and multiple layers of continuous networking were all considered.

The learning preferences in the current college student population and known advantages of social learning were combined with science and technology educators' preference for a best-practice pattern of experiential education and/or problem-solving activities, as well as a high impact practice recommended by the American Association of Colleges collaborative assignments [10-12]. The project team theorized that use of MR in active learning scenarios, supported by its ability to facilitate the desired elements, could improve the ability of students to master concepts by applying theoretical knowledge to practical lab activities.

In MR, synthesized elements can be made to obey physical laws. In this overlap of real and virtual environments, MR provides an immersive experience that can provide different points of view that were heretofore inaccessible to both learners and instructors. With MR a student can directly interact with abstract concepts; engage with variables in engineering equations; directly manipulate values, variables, and equipment getting real-time feedback of the impact of engineering laws on physical phenomena. This characteristic of MR enables engagement of more of the learner's senses in the process by increasing the types of sensory information processed and potential for learning. Rather than reading about a topic, visual input, and abstracting from there, or listening to an online or video presentation, visual and auditory input, students are able to engage with visual, auditory, motor, and spatial relations elements of the environment, immersing them in the content.

Implementation of this project began with the mixed reality platform being introduced to the Fall 2024 Electric Circuits Laboratory class. This paper details the methodology of implementing the project to date and discusses some initial results. A study was done by [13] highlighting the technical aspect of a remote lab involving use of more advanced circuit hardware for instruction than the study being reported on in this paper. The study in this paper, however, drills down to the fundamental level of designing MR labs using a breadboard along with power supplies, voltmeters and ammeters in building circuits, performing measurements and understanding circuit laws, which are crucial to building a solid foundation in Electric Circuits. The design of the MR labs was constructed to facilitate social interaction for enhanced learning.

Methodology

The undertaking involved developing mixed reality content to be used in the Circuit I lecture and Electric Circuits Laboratory of the Electrical and Computer Engineering program.

The methodology involved the following processes.

1. Determine the most troublesome concepts for students in Network Theory I and Lab.
2. Develop labs addressing students' conceptual challenges.
3. Develop mixed reality labs for implementation in the mixed reality space.
4. Beta test and refine materials multiple times.
5. Pilot penultimate MR elements with faculty and student users.
6. Develop means of assessing impacts (patterns for this and a detailed discussion of outcomes have been presented in a separate paper).

Some of the outcomes from step six are included in this paper to provide insight into the outcomes. See the separate paper by the same authors describing the research process and outcomes for a broader and extended discussion of findings.

In deciding concepts to focus on in developing mixed reality content, the faculty elected to address the following student challenges.

1. Connecting components on a breadboard in series and in parallel and measuring voltages across and currents through each component.
2. Proper connection of devices to common points of interconnection on the breadboard, referred to as nodes.
3. Application of superposition principles – how to properly remove and isolate sources for measurement and calculation of quantities.
4. Resistance in series and parallel circuits and understanding principles of current flow.
5. Theoretical understanding of key principles of electrical circuits including Ohm's Law, Kirchhoff's Law and Thevenin and Norton Theorems.

As a result, 4 labs were developed, each having a specific objective:

Lab 1: Breadboard Basics and Series Circuit
Objective: To understand the basics of series circuit construction on breadboard plus voltage and current measurements and Ohm's law.

Lab 2 Parallel Circuit Only Lab

Objective: To understand principles of parallel circuits, application of Ohm's law and measuring voltage and current in a parallel network.

Lab 3 Series/Parallel Lab
Objective: To exercise principles of parallel circuits, application of Ohm's law and measuring voltage and current in a series-parallel network.

Lab 4: Superposition and Thevenin's Theorem
Objective: To understand the use of the principle of superposition to determine voltage and develop Thevenin equivalent circuit.

The research was designed to have students self-assess before and after completing the collection of labs with scores ranging from 0 (no understanding) to 10(expert level), along with taking a pre and post skills test, which are reported on in a co-paper.

Implementation

The critical path for implementation was determined after much deliberation to be the use of the MR platform in both the Electric Circuits lecture for reinforcement of theoretical concepts and in the laboratory for help in developing skills in constructing and analyzing circuits.

Mixed Reality Environment Development

Pictures of components were submitted to the software developer for the creation of digital twins. Explanations of how the components work as far as adjusting settings, taking measurements, theories governing the values of measurements and the layout of how the breadboard is used were explained to the software developer.

Figure 1a shows the flowchart with development of mixed reality labs platform for integration in instruction. Figure 1b shows give more insight via the flow chart into the technical architecture development process involving engagement of the services of Serl.io. *The mockups are the 2D design and space layout given to the developers to conceptualize the framework, scene and interfaces. *Content assets are the 3D models, 2D images, voice overs, etc. that are used in the mixed reality scene/environment. This development process was iterative and involved close collaboration between Serl.io and the educational team.

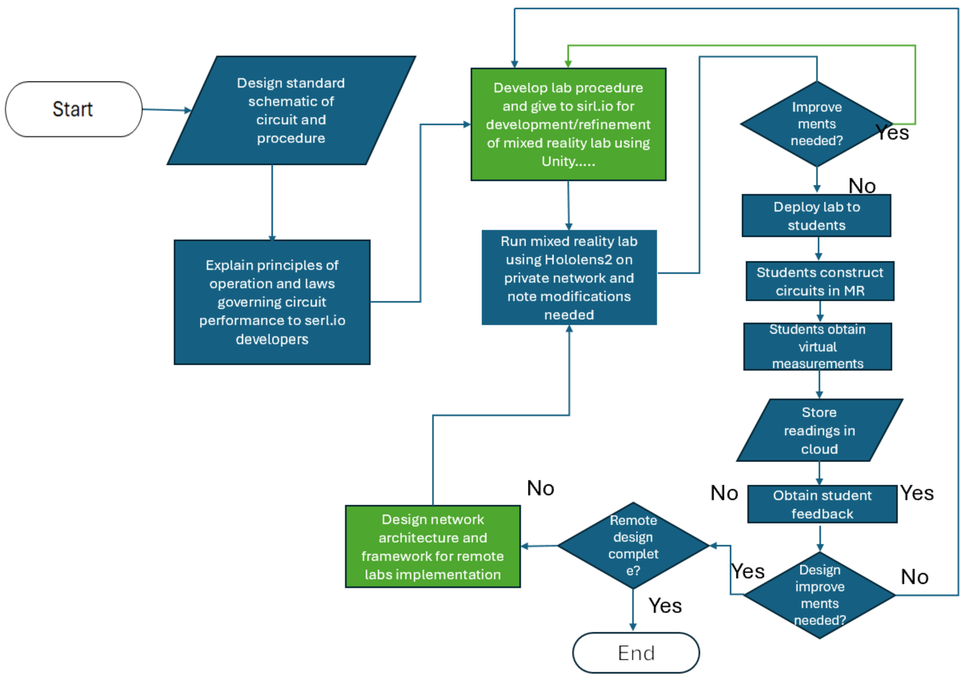

Figure 1a: Mixed Reality Lab Development for Instructional Integration

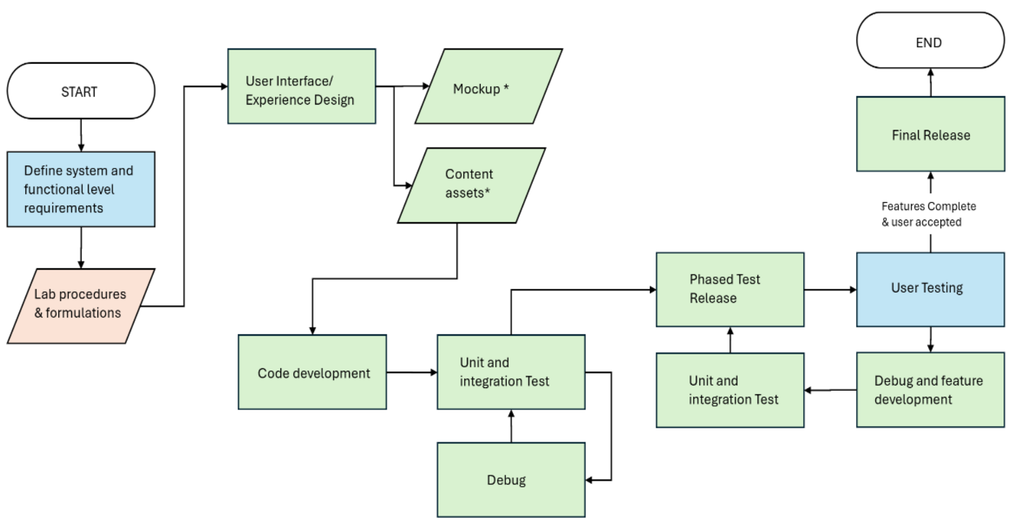

Figure 1b Mixed Reality Lab Technical Platform Architecture Development

The development of the mixed reality platform by Serl.io involved the following steps:

1. Define functional requirements, objectives and general user flow.
2. Perform Software and architecture design, including interface protocols and formats.
3. Create User experience(UX)/User Interface(UI) design and asset production. This includes 3D models, 2D sprites (images integrated into MR environment), audio and voice overs.
4. Develop Front end mixed reality content using primarily Unity/MRTK (Mixed Reality Toolkit/C#. Breadboard holes are associated according to node IDs. Components

(resistors and jumpers) are attached to holes (nodes). Multimeter probes will be able to identify the nodes it is contacting.
5. Adapt PySpice-PSpice circuit solver algorithm using Python and integrate into MR design [15,16].
6. Develop and implement backend using Microsoft Azure.

The mixed reality session involved use of the Microsoft HoloLens 2 headset. Figure 2 shows the network setup for a local session in which a single host computer would host session lobbies. Each lobby consists of a single lab group. Each member of the group would be assigned a headset. The HoloLens 2 headset itself has no special connectivity requirements; it contains a Wi-Fi 5 (802.11ac 2x2) adaptor and connects to the host computer using Wi-Fi. The headsets and local host computer must be able to see and connect to each other via IP addresses in the same network and the system needs to be able to access the Serl.io website and domain for it to work. In a session, four or five students working together in the environment could see each other and also see the virtualized instruments, instruction panels and components as well as each other's placement and manipulation of virtual lab equipment, components and panels. For example, if a student took a resistor off of the components palette and placed it onto the breadboard, other student participants in the group would see the student obtaining the resistor and the student's placement of the resistor onto the breadboard. Instruction panels for the virtual procedure were moveable for convenience.

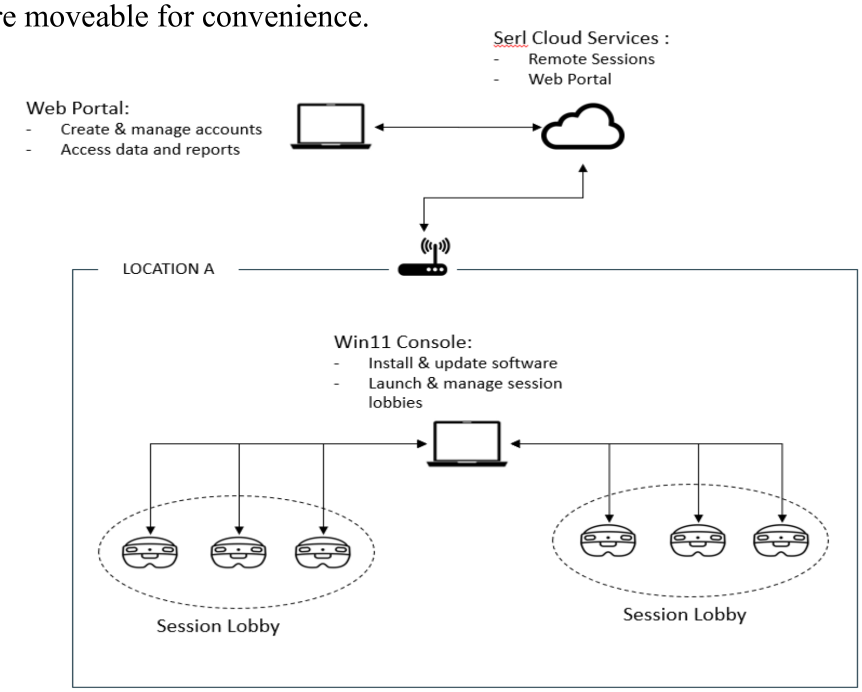

Figure 2: Network Configuration with Session Lobbies in single location

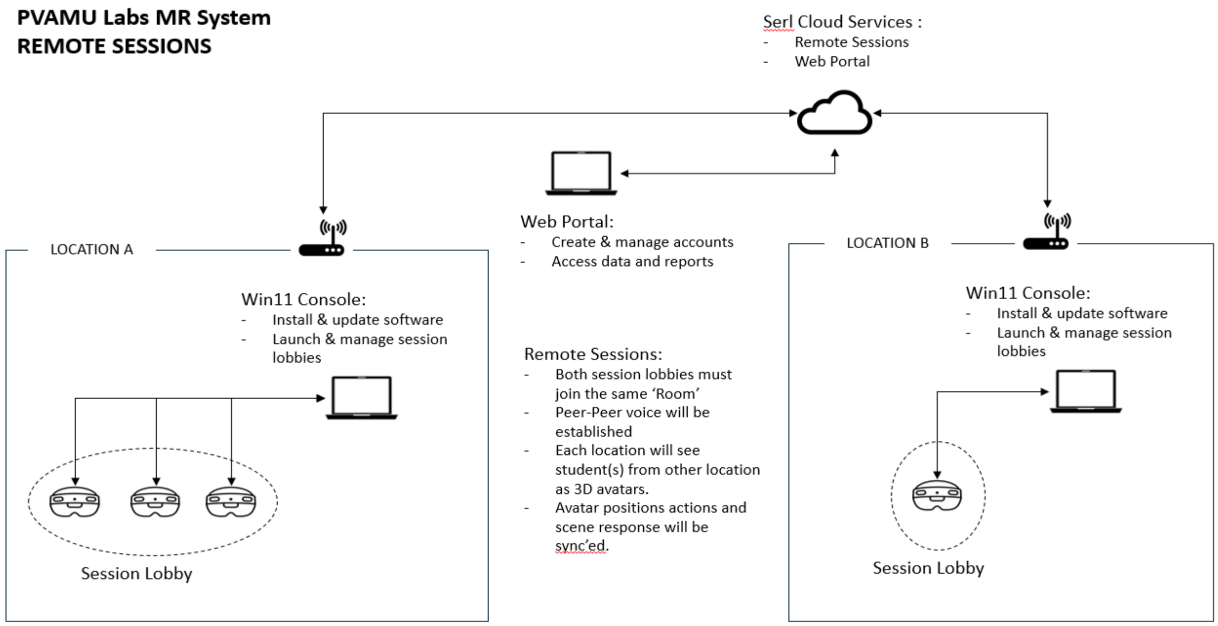

Figure 3: Network Configuration with Session Lobbies for Remote Labs Implementation

Figure 3 shows the setup for a remote lab implementation. Testing of the mixed reality labs performed remotely is an upcoming phase of this project.

The components used in the mixed reality consisted of a breadboard, resistors, jumpers, power supply, connection leads and meters. These components are fundamental to building circuits and measuring circuit parameters. They were needed for students to perform the lab as a virtualization of the real physical lab.

A depiction of the environment is made in the following figures (Figure 4 through Figure 6), corresponding to the implementation of lab 1. Figure 4 shows a breadboard, power supply to the left, power rails to which positive and negative leads from the power supply are placed and from where jumpers can be extended to the circuit to provide power. Jumpers are not used in this scenario, but resistors are connected directly to the rails. Also shown is a resistor across which a multi-meter is placed in a manner to measure voltage. The resistor is placed onto the breadboard by touching the holes in which each leg of the resistor would fit into then grabbing the resistor and moving the resistor to the vicinity of the holes and snapping it into place, or by specifying the coordinates of the holes into which the resistor would be placed. Locations on the breadboard are specified by breadboard column letter and row number. The ability to grab the resistor from the parts panel is what makes this project a mixed reality one. The component is virtual, and the person's hand is real. Mixed reality allows for the interaction of both. Of course, when the person grabs the component, there is no sense of feel, but the user can see the component move using the Hololens while physically moving one's hand to the location where the component is to be installed.

Figure 4 Power Supply and Voltage Measured Across Components in Series Circuit

When the measuring leads are connected across a component and a valid connection is made, the legs of the component will illuminate in green, as shown in Figure 1. They are connected manually by the user on the virtual supply.

When power is needed, the user presses the channel that the supply is to provide (there are multiple power channels). The value of the voltage is entered by pressing its numerical value on the virtual keypad of the virtual supply on/near the connection point.

Just as resistors can be moved, virtual measurement leads can be moved to where they will be used. Physical contact of the lead with the component to be measured is indicated by a green bubble appearing.

Laboratory instructions were given in the mixed reality environment. A portion of instructions are shown to the left of Figure 5. In the center there is a palette with resistors and jumpers that can be selected. The right portion of the figure shows the coordinates on the breadboard corresponding to the placement for the resistor selected.
The following is a summary of the procedure that was adapted and virtualized in the Mixed Reality platform for Lab1 for the students to follow:

Lab 1 Summary Procedure

1. *Select proper resistors and insert them into the breadboard according to the pattern of arrangement in the schematic shown (series circuit).*
2. *Apply inactivated power to the circuit.*
3. *Apply a voltmeter (multimeter set to measure voltage) across the supply and measure the source voltage.*
4. *Apply an ammeter (multimeter set to measure amps) in series in the circuit.*
5. *Turn ON the power supply and adjust it so that the output is 12V as measured on the Voltmeter. This is the source voltage V_s.*
6. *Measure the source current using the Ammeter and enter the current value on the Data Sheet (I_s for I source)* *Also measure the current through the 470,1000- and 1500-Ohm resistors and place the values in the table below.*
7. *Remove the Voltmeter from the power supply and measure voltages across each of the resistors in the circuit. Enter the voltage values for each resistor on the Data Sheet.*

8. *Now turn OFF the power supply.*

After collecting data, students submit their data sheets in the mixed reality lab by pressing "Submit Report."

Included with the lab were hardcopy instructions. Future implementations will include a calculations section to be completed following hard-copy instructions.

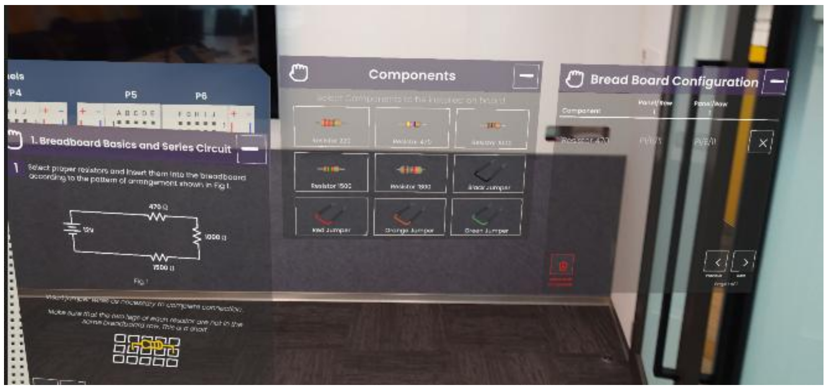

Figure 5 Virtual Instructions and Components for Selection

Ensuring proper understanding of how to measure voltage and current of components in a circuit is one of the objectives of the lab. Figure 6 below shows a virtual multi-meter being used to measure the voltage across a resistor with the virtual reading showing.

Figure 6. Virtual Measurement with Meter Recording Measurement

Implementation of the mixed reality lab was an iterative process that involved conveying to the software team the expectations, layout and technical considerations for the lab. It also involved going through the lab with the headset to evaluate procedural flow, feasibility and to ensure that progress was measurable, such as by having students submit virtualized results, and submit their lab in the virtual space when they completed it.

Social Interaction

The labs are designed to be socially interactive with students working together in a central location or remotely. In the case of remote labs, the students would select avatars to represent themselves. The remote labs implementation is a next step to be performed. In either case, the students can see each other or avatar representations of each other and interact with each other when implementing the labs. When a student places a component onto the breadboard, all the students have the opportunity to view the placement. The size of the breadboard is significantly enhanced to approximately 2 feet by 3 feet with the holes for connections significantly enlarged in size. The larger platform makes it easier for students to observe each other placing components into the breadboard and to troubleshoot connections. The visibility of the holes is better with the virtual breadboard than the physical breadboard due to the enhanced size of the virtual breadboard.

Results

Skills test pre-instruction mean was 46.66% with a standard deviation of 14.9 points while the post-participation mean was 58.56% with a standard deviation of 11.9 points. This difference was statistically significant at the 0.032 level.

Skills test and self-assessment results are being discussed more in depth in a separate publication being submitted to ASEE in which results from the Electrical and Computer Engineering mixed reality study and the twin Chemical Engineering study are discussed together. However, qualitative feedback received from students is described below.

At the end of the first lab, students were asked self-reflective questions. The following is a listing of the questions and a summary of the responses:

1. **Ease of Use: Discuss ease of use of the HoloLens. You can discuss issues related to how you felt; comfort or discomfort; use of the HoloLens while trying to run the experiment:**

Table 1: Ease of Use

Ease of Use	Details
Number of Students Responding	14
Number and Percentage of Mixed Responses	7 (50%)
Number and Percentage of Negative Responses	3 (21%)
Number and Percentage of Positive Responses	4 (29%)
Summary of Responses	The positive responses were that the experience was cool/smooth overall, and that the system got easier to use after getting used to and comfortable with the headset. Negative responses were a few experiencing headaches and feeling sick after using the system, network connectivity issues, difficulty in use of the headset or it being uncomfortable and resulting in eye discomfort.

2. **If you were to run a similar experiment in the lab, can you discuss whether you think that the mixed reality tool slowed you down, sped you up or did not affect the way in which you acquired data**:

Table 2: Speed of Use

Speed of Use	Details
Number of Students Responding	14
Number and Percentage of Mixed Responses	3 (21%)
Number and Percentage of Negative Responses	11 (79%)
Number and Percentage of Positive Responses	0
Summary of Responses	The majority of responses indicated that the system slowed the students down with their progress with the lab. Some responses indicated students were aware they were on a learning curve and after they became acclimated to working with the platform, they were able to progress quicker.

3. This lab sought to provide an immersive experience, to give an ability for social interaction and to enable remote learning. Can you comment on your personal experience regarding how the MR tool provided you with:

a. An immersive experience:

Table 3: Immersive Experience

Immersive Experience	Details
Number of Students Responding	14
Number and Percentage of Mixed Responses	0
Number and Percentage of Negative Responses	0
Number and Percentage of Positive Responses	14 (100%)
Summary of Responses	Student responses were all positive about the experience in immersion. They indicated a high degree of interaction between group mates and ability to interact with the virtual equipment. Some stated the experience was interesting, enjoyable and engaging. There also was a positive comment about the enlarged equipment in the environment being of assistance in the lab instruction process.

b. An ability for social interaction:

Table 4: Social Interaction

Social Interaction	Details
Number of Students Responding	14
Number and Percentage of Mixed Responses	0
Number and Percentage of Negative Responses	1 (7%)
Number and Percentage of Positive Responses	13 (93%)
Summary of Responses	The students' comments on the ability for social interaction were almost 100% positive. They valued the high degree of social interaction the MR lab provided. One student found it difficult to work with others in the setting.

Discussion

Challenges faced in the development of the labs were primarily logistical. We planned to first implement the platform in the Circuits lecture; however, due to class scheduling conflicts, this plan could not be realized. Consequently, the first implementation was carried out in the Circuits Laboratory.

Another challenge we overcame was where to implement the labs. We were able to secure a dedicated space and the assistance of IT with establishing an isolated and dedicated network in which to run the mixed reality sessions.

Feedback from implementation of the mixed reality lab with Circuits Labs students was quite helpful. The social interaction that mixed reality labs promote is useful in helping students develop social skills in the midst of adverse circumstances that would not enable them to meet in person. This confirms the findings of study [14] which states that many aspects of social interaction transfer into virtual reality and can be adjusted and enhanced as necessary.
Feedback from students highlighted the need for an orientation lab for the students devoted solely to familiarizing them with working with the virtual instruments as the initial lab instead of them becoming oriented while conducting lab 1, which slowed them down. Some of the students were insightful enough to realize that they were slowed down due to overcoming a learning curve with using the technology but indicated future use after familiarization would go quicker and smoother.

Consideration of the ergonomics of using the mixed reality platform, in particular the HoloLens2, needs further evaluation, as a few students reported headaches and being uncomfortable with using the HoloLens2. We will, therefore, factor in having the students take intermediate breaks from wearing the headsets to reestablish equilibrium if they need to while discussing the theoretical aspects of the lab with each other in physical reality and performing calculations to reinforce concepts to validate their findings before returning to wearing the headsets and commencing with the mixed reality labs.
It was observed that the students' ability to follow the virtualized procedure was hindered by the availability of the hard copy instructions, which seemed to impede their progress with the lab; therefore, to keep students focused and progressing, we propose procedural instructions only be delivered virtually in future implementations. The students are able to submit their measurements virtually as they are logged. We plan to have an accompanying hardcopy table for recording measurements/calculations of lab results. We propose having them take intermediate breaks from wearing the HoloLens 2 headset during which they can complete calculations to validate their measurements.

Future implementations in this study will involve the students completing labs 2 through 4 which will enable the collection and evaluation of more data and determination of the usefulness of the mixed reality labs for improvement in learning circuits.

Conclusion

We developed 4 mixed reality labs and were able to implement Lab 1 in the Electric Circuits Laboratory in the Fall 2024 semester. The responses from students were mixed with an indication of need to consider orientation to the use of the platform in advance of the lab and student comfort.

There were responses suggesting improvement in learning. Future implementations will also involve further analysis of pre and post skills test data and pre and post self-assessment data to gage overall effectiveness in contributing to learning circuits.

We recognize that MR lab costs per student can be a deciding factor in determining whether this tool could be readily implemented in an electrical & computer engineering context. To that end, one of the project goals is to fully understand the costs that would go into development and implementation. That is an on-going process as some revisions are underway and there has only been one semester of implementation which was limited to two courses. That time frame is insufficient to arrive at a complete understanding of monetary investment necessary for continued use.

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