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Initial Results of Chemical and Electrical & Computer Engineering Mixed Reality Lab Modules – Work in Progress

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Abstract

This Work in Progress paper describes initial findings from an educational innovation project which deploys mixed reality (MR) modules in Engineering instruction as holographic digital twins of laboratory equipment. The NSF-funded undertaking is based on findings from a pilot study for chemical engineering completed with institutional resources. Under the NSF grant, the scope was expanded and MR assets, the digital twins, were developed for both Chemical Engineering and Electrical and Computer Engineering instruction. The project research focuses on learning and engagement impacts from use of MR modules in classroom and lab settings for both disciplines. The Chemical Engineering MR digital twin is based on a fluid flow in pipes lab, featuring a pipeline network having different pipe diameters, lengths, roughness, and fittings. Students are able to measure pressure drop as a function of fluid flow rate through the different runs of pipe. The Electrical and Computer Engineering MR asset is based on a combination of breadboard, power supply, voltage/amp meter, resistors and circuit connection cables. Students are able to create various electrical circuits using the breadboard and associated components and measure voltage working with series and parallel concepts and Thevenin, Norton, and superposition theorems. With both MR assets, manipulation, adjustment, and experimentation are possible simulating real-world processes and outcomes. Data capture and analysis functions also are present. Students in a Chemical Engineering course and an Electrical and Computer Engineering lab completed two pre- and post-instruction assessments specific to the course topics for which MR assets were used. The first was a short quiz intended to measure learning in the topic and the second was a self-assessment designed to gauge perceived skill in relevant areas. Students were also asked to complete a brief qualitative feedback survey following MR use. Quantitative data analysis involved descriptive and comparative processes, as applicable. Constant comparative analysis for theme identification was employed with qualitative input. Statistically significant increases in levels of understanding, on pre- and post-instruction self-reports from students, and for objective skills tests were found. MR instruction was able to facilitate an interactive, collaborative, problem-based approach to learning in courses. Implications for Engineering education, grounded in the original literature-based theory, are described.

Key words: mixed reality, virtual reality, holograms, digital twins, active learning, educational technology, remote learning, chemical engineering, electrical engineering, computer science, laboratory equipment, laboratory instruction, formative assessment.

1. Introduction

During the COVID-19 pandemic, when remote instruction was mandated by institutions of higher education, laboratory experiences, which are traditionally a practical, in-person activity, were offered virtually. There were many ways in which different institutions dealt with this issue. In the Prairie View A&M University (PVAMU) Chemical Engineering Department (CHEG), students were provided with videos of the instructors describing and displaying lab equipment and performing the lab experiments for the course. Representative data for the experiments were provided to the students for their analysis and they were asked to combine what they learned from the video and their analysis of data to write lab reports. While an effective approach under the circumstances, it lacked the first-person, immersive experience that is crucial to developing deeper knowledge and understanding (Bonasio, 2019). This deficit was an instructional limitation as was faculty lack of videography expertise which made the remote instruction provided by video vary in quality by course section and from course to course. Lacking videography expertise and professional level equipment also presented faculty with multiple technical and logistic challenges when presenting engineering labs as video content. Brainstorming regarding possible solutions led to a desired approach, digital content that would allow virtual manipulation of lab equipment and completion of experiments using digital twins. The intention was that these representations of physical equipment would be capable of different uses and access by multiple parties simultaneously.

In parallel and quite separately from the Chemical Engineering experience, instructors in the Electrical and Computer Engineering Department (ECE) observed that the way the students responded to learning opportunities changed during the COVID-19 pandemic when they migrated to fully online instruction. Content comprehension was adversely affected. Students would listen to lectures but could not demonstrate understanding of what was taught. It was this circumstance that caused the ECE instructors to discuss potential for a virtual reality system to deliver instruction in a manner that was more appealing and included engagement with the process versus observation.

Following the pandemic, a team of PVAMU Chemical Engineering faculty secured institutional funding for a pilot project in use of mixed reality lab instruction. Mixed reality superimposes computer-generated holograms over real-world objects or environments allowing real-time interaction between physical and computer-generated elements. The user is still aware of the physical environment, which does not interact with the holograms, and can engage separately with real-world or holographic elements. Holograms, though, can only be manipulated by user hand gestures, voice, and gaze. Results of the pilot are described in Antoine, Martin, and Gabitto (2024). Based on findings from that undertaking, a team of engineering faculty representing CHEG and ECE disciplines submitted a proposal to the National Science Foundation (NSF). This paper reports first year findings from the activity funded by NSF.

2. Solution Selected

While a global pandemic might be considered an unlikely impetus for consideration of unorthodox teaching and learning strategies, that was the case. Mixed reality was chosen by the project team as an immersive technology capable of facilitating remote learning in engineering courses based on: (1) its potential for supporting knowledge acquisition, (2) aligning with learning preferences of 21st century students, (3) providing permanent but adaptable settings with real-world manipulable properties, (4) safely expanding potentials beyond those of real-world settings, (5) facilitating interactive learning, (6) transcending some practical limits, and (7) providing learning and creative opportunities for faculty. Classroom and lab modules with virtual equipment, virtual scenarios, or use of portions of mixed reality to bolster instruction, akin to using a video clip to supplement a class, were envisioned with the intention of enhancing knowledge acquisition and competence building.

In these considerations, the definition of knowledge employed was from Davenport and Prusak (1998), "a fluid mix of framed experience, values, contextual information and expert insights that provides a framework for evaluating and incorporating new experience and information." Tiwana's (1999) pattern for characterizing knowledge as two main types, explicit and tacit, was also employed. Explicit knowledge is conscious and 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. To communicate beneficial knowledge and for students to acquire it, experiences that include explicit knowledge, are interactive and repeatable, and that are culturally and/or contextually relevant so that individuals can create meaning for themselves (tacit or implicit knowledge) are required. By providing the right learning environment, knowledge acquisition, at both explicit and implicit/tacit levels can occur. This transformation develops personal competence, which, when appropriately guided by more skilled parties (e.g., instructors) can result in the ability to perform activities to the standards required in professional environments.

There is also a confluence of factors that are affecting the way 21st century students learn. General access to digital technology, the ubiquitous use of social media, and the prevalence of smart devices that are mobile and interactive have enhanced connectivity. Students now have ability to be engaged with digital content at will. Immersive technologies from augmented reality (AR) to virtual reality (VR) can be deployed to great effect in this milieu as science and engineering educational platforms. The learner can engage representations of the physical world in ways not possible for them to experience in a physical lab (e.g., stand inside operating machines or living organisms, safely perform maximum stress tests). The virtuality-reality continuum (Figure 1, Milgram & Kishino, 1994), illustrates ways a learner can be engaged with a digital, synthesized environment. This can totally exclude the physical world, as virtual reality at the extreme right of the spectrum in Figure 1 (e.g., the Holodeck of Star Trek), or locate the learner in the physical world with digital elements superimposed allowing the user to interact with them in a physical space set up for that purpose. The second pattern is called mixed reality and can extend from a limited presence and functionality in a real world setting to being the predominant context but still presented superimposed on the real world.

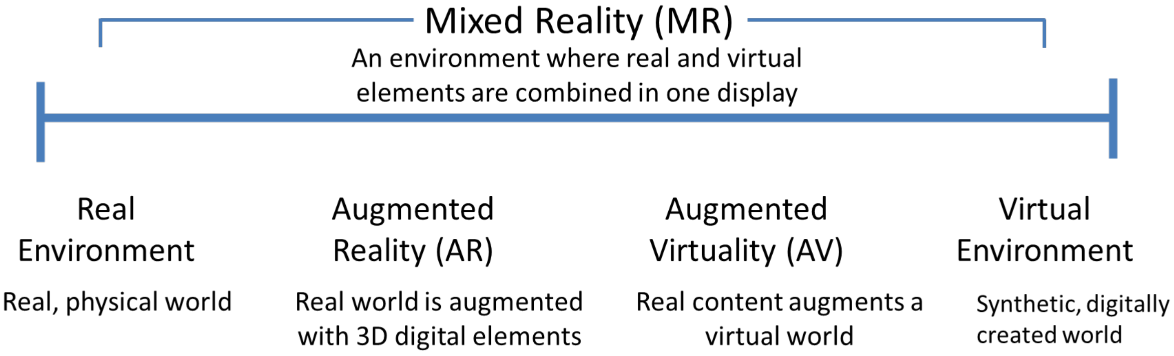

Figure 1. The virtuality-reality continuum (after Milgram and Kishino, 1994)

In mixed reality (MR), "smart" concepts are employed, in that the synthesized elements can be made to obey physical laws. In this overlap of real and virtual environments, MR provides an immersive experience with potential for different vantage points that were heretofore inaccessible to both learners and instructors. With MR, a student can enter a working machine or directly interact with abstract concepts like engaging with variables in engineering equations, directly manipulating them and getting real-time feedback of the impact on physical phenomena. This characteristic of MR enables engagement in problem-solving or even creative investigation and of more of the learner's senses in the process by increasing the types of sensory information processed. This expands the potential forms of learning and, possibly, the potential for learning (Jacobson, 2013; Lu and Liu, 2014; Santos et al., 2016). Rather than reading about a topic, experiencing visual input, and abstracting from there, students are able to engage with visual, auditory, motor, and spatial relation elements of the environment, immersing them in the content. MR also can, as just noted, expand potential for experimentation since the environment is virtual and all but eliminates physical risk.

In the US, 66.6% of college students are aged 24 years and below (Hanson, 2022). Thus, the majority of constituents being served in higher education are millennials and Gen Z. Different generations are motivated in different ways and prefer to learn in different ways. For the current majority demographic it is important to recognize the following: (1) Millenials/Gen Z want to interact throughout training sessions; (2) They are used to having a voice and expect to contribute; (3) Not only do they expect to learn but they expect to have input into the process and have fun while

Table 1: *Instructional Strategies and Mixed Reality*

Instructional Strategy	Mixed Reality Fit
Develop self-assessment items	Provides immediate feedback
Provide opportunities for group work	Remote participation available once users have a reliable internet connection
Incorporate technology: create a multimedia environment and connect to learners through social media	Elements of gaming, inherent connectivity
Give them group projects to complete	Collaboration natively enabled with participants wearing headsets having access to the same running simulation
Include ways learners can customize the course . . . While providing a very structured environment (clear objectives and standards).	No code/low code options available for participants (Microsoft Dynamics, PowerApps, Guides, MR Toolkit) Coding skill required (C++, Unity)

learning; and, (4) They network out of the classroom and expect to network in the classroom as well. MR allows each of the above patterns to occur similar to virtual gaming. The potential for social interaction makes MR an environment that incorporates social learning theory, the notion that people learn from interacting with others (Bandura, 1971; Gee, 2003, 2004), as an essential element. Table 1 provides a summary of how the instructional strategy for Millenials/Gen Z can fit with the application of MR as a tool for instruction.

Researchers have argued that implementing MR in active learning scenarios can directly and immediately improve the ability of students to make insightful connections between theory and practice (Antonova, 2013; Bonasio, 2019). The field of engineering as a whole employs the understanding and application of abstract concepts to solve a problem by either creating a physical device or by stitching together seemingly unrelated subject matter to achieve a deliberate, ordered process. Engineering students are expected to "jump" from theory to practical application. In fact, low rates of knowledge transfer from theory to practice, even by students who excel in school, is a major driver in looking to an immersive technology to address this shortcoming. MR can provide inherently immersive experiences and circumvent practical limitations such as expense, logistics, scale (large or small), access, and risk. For a well-constructed, virtual environment, the setting itself contributes to explicit-to-tacit knowledge transfer in a realistic, accurate, and safe environment while expanding potential for access in respect to number of parties actively engaged and/or eliminating time limits. There is evidence showing that test scores among students using immersive technologies improved by up to 22% (Santos et al., 2016). Students learn to learn by themselves, to work in groups, to solve problems and push boundaries. MR sets the scene for group interaction and "play", thus creating group and organizational identity and enabling innovation and adaptability to changing circumstances (Barsalou, 2008).

A factor that has often been cited by students at Prairie View A&M University as a barrier to effective teamwork is the requirement that students be physically present in the same location. For an institution at which many of our students are "non-traditional," commute to school and/or have work and family obligations, this is not trivial. Giving students access to MR tools immediately addresses the physical location requirements by allowing remote, yet immersed and real-time interaction. Thus, MR can address a variety of challenges in modern higher education by providing an accessible, digital twin of real-world entities while connecting learners, facilitating collaborative, problem-based or play-like exploratory learning (Barsalou, 2008), and engaging a wide range of the learners' physical and motor senses.

Another important aspect of MR educational content is the effect on the instructor. Engaging with this technology provides opportunity for reassessment of how to teach engineering concepts, can expand the range of instructional offerings, has been shown to enhance effectiveness of instruction (Jacobson, 2013; Lu and Liu, 2014; Santos et al., 2016), and creates opportunity to increase creativity because the technology can be leveraged to create a wide variety of virtual experiences.

3. Research Purpose and Questions

Several research purposes were envisioned during the design phase of the MR modules for CHEG and ECE courses. These were determining: (1) whether MR modules are effective as instructional tools for fluid dynamics and electrical circuits courses; (2) whether MR instruction is as or even more effective than traditional engineering instruction; (3) whether any efficacy demonstrated is universal or varies by ethnicity, race, gender, and first-generation student status; (4) what applications of mixed reality do students desire in engineering instruction; and (5) whether students return to reuse MR lab modules and what the purposes are for that reuse. This presentation addresses the first research question and to a limited extent the fourth. Data relevant to the second and third questions were gathered but the number of courses in which the MR applications were enacted in the first year of the undertaking and enrollment in those courses would not support the desired comparisons. Data gathering in subsequent semesters will be necessary to achieve sufficiently sized response pools for statistical power. Data gathering relevant to the fifth research topic was prevented in the first year of implementation by several logistic challenges.

4. Research Methodology

Surveys were employed to gather multiple forms of information. Pre- and post-instruction responses to the same questions were requested in respect to instructor-identified skills relevant to and involved in the course modules. A pre- and post-instruction survey pattern was also employed for the self-assessment in which students rated their skill in topic areas derived from the course objectives. The final form of data considered in this paper is self-reports about student experience with the modules referred to herein as self-reflection questions.

4.1 Instrument Development

Each of the question sets employed was developed by the project team. The process for development of the queries included on the instruments was collaborative. The basis for the skills tests and self-assessments was the course instructional objectives. The skills tests, one for each course, were developed as multiple-choice instruments with four possible responses for each question. The initial question sets were devised by the faculty in the discipline with revisions made based on comments and suggestions from the other faculty working on the project and the research consultant. The initial set of self-assessment queries for each course was developed by the consultant and reviewed and revised in project team meetings. The self-reflection question set was adopted from the project pilot. It had proven to yield information of the type desired in that undertaking and following review by the project team in a group meeting was adopted for use in this project.

4.1.1 Validity and Reliability

The skills test, self-assessment, and self-reflection questions have face, construct, and content validity (Middleton, 2022). This resulted from development by faculty experts who teach in the field, their peers who teach in another engineering field, and the research consultant who holds a doctorate in Education with an emphasis in curriculum and instruction and who taught graduate level assessment and research courses.

The institution provides its faculty seminars in instruction and assessment conducted by the Center for Teaching Excellence as part of continuing faculty development. Insight from that professional development and the expertise of the research consultant was employed. The group also had a high level of instructional experience in higher education. For all members, including the research consultant, experience ranged from six years to over 40 years. The parties devising the question sets were also the individuals who designed the course MR module, so they had extended and detailed understanding of the digital context to be used in instruction. The faculty who were content-area experts took the lead in CHEG and ECE material development but were assisted by their colleagues on the project, faculty members in the other discipline and the external research consultant who had collaborated with them to develop the project plan and the MR asset descriptions, diagrams, and story boards.

These processes provided the question sets the forms of validity noted above. Face validity, the suitability of the content (Middleton, 2022), was derived through development by content area experts with review and suggestions provided by persons with training in assessment and extended experience in higher education instruction. Construct validity, having indicators that match the construct to be measured, occurred as the assessments addressed specific, measurable concepts like calculations, ability to define a concept and ability to complete a process, that were developed directly from the list of ideas to be taught. Content validity occurred as all the intended instructional outcomes were addressed in the queries based on reliance on the specific and differentiated instructional goals. In addition to this, the self-reflection questions have reliability (i.e., producing consistent, dependable and repeatable results) based on a pilot project in which they produced the desired pattern of responses.

4.2 MR Module Implementation

Both the CHEG and ECE faculty developed four lab modules for use in mixed reality. Each was a full lab exercise with instructions, illustrations and visuals provided as necessary, manipulation of equipment and other elements, experimentation, formulas and calculation patterns, and prescribed information to generate regarding the process completed. The CHEG courses targeted during development focused on fluid mechanics while the ECE courses focused on electrical circuits. In the fall semester of 2024, one module for each discipline was implemented. This paper reports on the outcomes from that process while details of the MR holograms created for the two disciplines and the lab processes enacted are detailed in two other ASEE papers by the same authors (Antoine, et al., 2025; Foreman, et al., 2025).

4.3 Data Gathering and Analysis

There were four forms of data gathered. The first was demographics for the course enrollees. Another was a general skills assessment completed as a pre- and post-instruction measure. The skills assessment had 16 items for the ECE class and 14 for the CHEG course. Both focused on items taught in the course and directly applicable to the modules deployed. This pattern made it possible for the overall learning achieved as well as the learning specific to the module to be measured. A self-assessment was also administered in a pre- and post-instruction manner. It asked the students to rate their perceived level of skill or understanding in respect to 15 course-objective-related topics using a ten-point scale ranging from no understanding to expert level. Like the skills assessment, the questions had a course wide scope with an imbedded set of MR module-specific queries. The final form of data was short written responses to a group of self-reflection queries. These sought information about the ease of use and value in the MR application, the party's experience with the application, and suggestions for improvement.

Descriptive and comparative statistics, as applicable, were employed with the quantitative data and the constant comparative method (Kolb, 2012) with qualitative data. The presence of multiple streams of data regarding the same construct facilitated triangulation and a broader and richer understanding of outcomes.

5. Findings

Findings from each of the forms of data will be described below. The results from the CHEG and ECE courses will be described separately as they are different content areas taught by discipline-specific faculty. When applicable, insights from more than one data set will be employed in interpretation of the general findings.

5.1 Sample Versus Population

The CHEG course had an enrollment of 24 students all of whom persisted through the semester. Self-reports indicate that these persons were four males and 20 females the majority of whom identified as non-Hispanic. Racial identities were 18 African Americans, three Hispanic/Latina/o, one international student, and two who preferred not to respond. Since 24 submissions were received both pre- and post-instruction for the skills and self-assessment question sets and post-instruction for the self-reflection questions, the CHEG sample is fully representative of the population.

The ECE course had 17 enrollees, four of whom identified as female and 13 as male. One female and three males identified ethnically as Hispanic/Latinx and racial identities were ten African Americans, one Asian, four Hispanic/Latina/o, one multi-racial, and one White. Pre-instruction skills test submissions were received from 12 parties and post-instruction submissions from 14. Pre- and post-instruction response rates for the self-assessment were 10 and 15 students. The post-instruction samples can be considered representative of the population as gender and race proportions were similar but the pre-instruction samples, with lower counts, resulted in over and under sampling as percentage of respondents at several points. While not strongly skewed, the variance and smaller sample size mean the ECE sample was not fully representative.

5.2 CHEG Course Data

Description of the outcomes for each of the three forms of data gathering for the CHEG course follow.

5.2.1 CHEG Self-Assessment

The self-assessment queries covered topics addressed throughout the course. The general results were strongly positive. Group means increased for all 15 questions while standard deviations decreased, in some cases by over 50.0%. All but two of the differences were statistically significant (Table 2).

TABLE 2

Fluid Dynamics Self-Assessment Outcomes

Prompt	**Pre-Part.**		**Post-Part.**		**Sign.**
	Mean	***SD***	***Mean***	***SD***	
a. I can define fluid pressure drop.	6.52	1.92	8.04	1.67	0.006
b. I can define the term “head” as it relates to fluid dynamics.	7.30	2.27	8.38	1.95	-
c. I can name three or more fluid properties.	7.26	1.72	8.52	0.97	0.004
d. I can name two or more flow regimes.	5.95	3.20	8.50	1.53	0.006
e. I can list two or more devices that can be used to measure fluid pressure.	7.78	2.17	8.46	1.22	-
f. I can explain how fluid turbulence in pipes is related to properties of the fluid flowing through the pipe.	5.64	2.82	7.75	2.15	0.006
g. I can explain how fluid laminar in pipes is related to properties of the fluid flowing through the pipe.	5.13	3.04	7.92	1.89	0.0005
h. I can use the continuity equation to calculate the flow rate of a fluid.	5.78	3.15	8.67	1.43	0.0002
i. I can calculate pressure drop and head loss in pipe flow using the mechanical energy balance equation.	5.45	2.71	8.58	1.08	0.0001
j. I can explain the relationship between pressure drop and the geometrical parameters of a pipe.	5.13	3.00	7.58	1.71	0.001

TABLE 2

Fluid Dynamics Self-Assessment Outcomes

Prompt	Pre-Part.		Post-Part.		Sign.
	Mean	***SD***	***Mean***	***SD***	
k. I can calculate friction factors for different pipe materials and roughness using Moody charts.	2.35	2.71	7.71	2.21	0.0001
l. I can estimate energy loss in pipe systems of varying diameters and lengths.	4.00	2.90	7.96	1.60	0.0001
m. I can conduct experiments to measure pressure drop in pipes.	4.96	3.45	8.92	1.19	0.0001
n. I can explain the concept of minor flow losses in fluid mechanics.	3.91	2.83	7.21	1.61	0.0001
o. I can analyze the combined effect of friction and minor losses on pressure drop in complex pipe networks.	3.13	2.59	7.28	1.70	0.0001

The findings confirm the students' sense of ability increased across the general spectrum of instructional objectives. Nearly all the items were directly related to the content of the MR modules since early content in the course was a foundation for more specific applications presented later in the semester. There were, though, two items on the self-assessment that were not required knowledge to complete the MR lab module. Those were items b and e in Table 2, neither of which proved to be statistically significant in respect to increases in perceived ability. Removing those from consideration isolates the measures taken specific to the module content. It also results in a strong case for instructional effectiveness as there was a pronounced to very pronounced change in perceived ability as indicated by the p values for the pre- to post-instruction comparisons. While this cannot be interpreted as definitive proof that the MR modules where the cause of the change since there were many other contributing factors like course curriculum, classroom instruction, time students committed to study, etc., it is evidence that the MR experiences were associated with extensive and substantial increases in perceived skill and understanding.

5.2.2 CHEG Skills Test

The skills test for the CHEG students included 14 items. They were multiple choice questions with four possible responses for each. As noted above, they required parties to recognize definitions, outcomes of processes and the correct label for those, and to complete calculations. The group mean for the pre-instruction administration of the test was 38.39 with a standard deviation of 26.55 points. The number of students completing the pre-instruction test was 24. The post-instruction test was completed by the same 24 parties with a group mean of 70.50 and a standard deviation of 13.54 points. The difference in means proved to be statistically significant at $p = 0.0001$. This verified that the course produced significant increases in knowledge but the extent to which the

MR module contributed could not be isolated. However, isolating the queries relevant to the MR module content was possible like it was for the self-assessment. Removing them from the calculations had no impact on the level of significance for comparison of pre- and post-instruction measures. Like for the self-assessment, this cannot be understood to indicate the MR activity was the direct or only cause but it is a second measure in which the MR modules were associated with a highly significant outcome. In this case, objective measures of required skill.

5.2.3 CHEG Self-Reflection

A total of five questions, one with three parts, were asked on the self-reflection instrument. Informants provided short written responses. The topics were ease of use, pace (i.e., whether the MR application impacted time to completion of tasks), perceived differences in consideration of data, and whether the experience was immersive, interactive, and facilitated collaboration. A final question asked for additional comments the student would like to make.

Ease of use responses addressed three primary themes, broad responses about the MR module, comments regarding the comfort of the Hololens headset, and comments regarding impact on physical senses and wellbeing. The general response was that the MR approach was helpful, facilitated learning, and was “cool.” The Hololens equipment received mixed reviews from easy of use. It was seen as comfortable by some parties, difficult to set up by others, “not big hair friendly,” and difficult to don and wear or uncomfortable. It appears that Hololens headsets may not be as universally adaptable as the manufacturer hoped. A consistent theme arose in respect to physical senses and wellbeing. More than half of the students reported a sense of disorientation, eye strain, and/or development of a headache following extended use of Hololenses. Several suggested this was related to the “strange pattern” that occurred in the background of the projection of the digital twin.

Only one student felt the experimental pace was slower using the Hololens headset and MR module. Nearly half of the informants felt it made the process quicker to complete while remaining responses were noncommittal or unsure. Those who commented on possible slow downs felt they were a product of learning to use the equipment rather than use of an MR environment.

The consensus regarding data was that the MR platform, which included automated capturing and display of data points, made that process more efficient. Some students stated that the data was easier to read and therefore likely to be more accurate than they could gather in a physical lab experiment. Others found the data display helpful as it isolated all the items they needed in one location. Students individualized the way they captured data points some writing them down, others taking screen shots, and still others printing the information.

The survey query did not define what was meant by an immersive experience. This contributed to some variation in responses but the general perspective was that the MR module presented a real-world experience involving manipulation of virtual “equipment” and its elements and discussion of processes and patterns. Descriptors used in responses were “cool,” “engaging,” “wonderful,” and “fun.” To quote one informant, “It genuinely felt like we were physically in the lab” with another stating “It helped me see and understand the project better.”

Student responses mixed consideration of the interactive nature of the experience and ability to facilitate collaboration. Summarizing examples of responses follow. “Very interactive, had a good time collaborating with classmates and learning from others.” “My group members and I were able to do multiple things at once” and “I got to interact with other classmates and learn from them and their tactics” which included use of “problem solving skills as a team.” “You have to communicate with your team when to move the nozzles and what else to do,” “we were all working at the same time, not just one person moving.” These statements indicate the MR module was able to facilitate an interactive, collaborative, problem-based approach to learning for the course.

Responses to the additional comments query were statements that the module was “fun” and “amazing” as well as requests for use of MR for other lab experiments with one exception. That exception was a party who returned to the theme of discomfort and noted s/he “wouldn't recommend [MR] for people with motion sensitivity.”

5.3 ECE Course Data

Description of the outcomes for each of the three forms of data gathering for the CHEG course follow.

5.3.1 ECE Self-Assessment

Like for the CHEG course, the ECE self-assessment queries covered topics addressed throughout the course. The general results were positive. Group means increased for all 16 questions while all but one of the standard deviations decreased, in most cases between 15.0% and 33.0%. However, most of the differences were not statistically significant (Table 3). One reason for this was the

TABLE 3

Electrical Circuits Self-Assessment Outcomes

Prompt	**Pre-Part.**		**Post-Part.**		**Sign.**
	Mean	***SD***	***Mean***	***SD***	
a. I understand how to make interconnections on a breadboard.	7.20	2.04	8.60	1.50	-
b. I can explain how isolation between nodes works on a breadboard.	6.00	2.61	8.27	1.81	0.0169
c. I can construct a series circuit on a breadboard by following a schematic diagram.	7.70	2.10	8.60	1.67	-

TABLE 3

Electrical Circuits Self-Assessment Outcomes

Prompt	**Pre-Part.**		**Post-Part.**		**Sign.**
	Mean	***SD***	***Mean***	***SD***	
d. I know how to measure voltage across an element in a series circuit.	7.40	2.65	8.33	1.85	-
e. I know how to measure current in a series circuit.	7.30	2.15	8.27	2.29	-
f. I can construct a parallel circuit on a breadboard by following a schematic diagram.	7.89	1.73	8.47	1.54	-
g. I know how to measure voltage across an element in a parallel circuit.	7.00	2.93	8.60	1.58	-
h. I know how to measure current across an element in a parallel circuit.	6.70	2.72	8.07	1.84	-
i. I know how to apply circuit laws/Ohm's law to solve for quantities such as current through an element, voltage across an element, and total resistance in a series/parallel combination circuit.	7.10	2.88	8.13	2.31	-
j. I know how to identify an open circuit.	6.70	3.66	8.20	2.69	-
k. I know how to identify a short in a circuit.	5.80	3.22	8.00	2.61	-
l. I know how to calculate R_{Thevenin} for a circuit.	5.60	3.41	7.33	2.69	-
m. I know how to determine/measure V_{Thevenin} for a circuit.	5.50	3.44	7.33	3.03	-
n. I know how to apply the principle of superposition to a circuit to determine an unknown quantity (e.g., voltage, current).	5.50	3.26	6.40	3.07	-
o. I know how to calculate/measure R_{Norton} for a circuit.	4.90	3.21	7.00	3.14	-

students were very confident in their ability pre-instruction. Of the 149 ratings submitted, 26 were the highest possible, a ten on a ten-point scale. There were also 11 ratings of nine and 37 of eight. That is a total of 74 or 49.7% of the pre-instruction submissions occurring in the upper quintile of the scale. A second factor contributing to the limited volume of statistically significant findings was the small sample, ten parties pre-instruction and 15 post-instruction. Increases in self-assessment scores would have needed to be above two points with decreased standard deviations for significant results to occur given the size of the sample. Most of the increases were in the one to one-and-a-half point range. The only significant finding had a pre- to post-instruction difference in group mean of 2.27 points and a decrease in standard deviation of 0.81 points.

5.3.2 ECE Skills Test

The skills test included 16 items. They were multiple choice questions with four possible responses for each. Like for the CHEG course, they required parties to recognize definitions, outcomes of processes and the correct label for those, and to complete calculations. The group mean for the ten submissions on the pre-instruction administration of the test was 46.66 with a standard deviation of 14.91 points. The post-instruction test was completed by 15 parties, which included eight of the original ten respondents, with a group mean of 58.56 and a standard deviation of 11.85 points. The difference in means proved to be statistically significant at $p = 0.0316$. This verified that the course produced significant increases in knowledge but the extent to which the MR module contributed could not be isolated. However, isolating the queries relevant to the MR module content was possible as has been described above for the other assessments. Like the other cases, the pre- to -post-instruction comparison remained significant in the same value range. Thus, the MR module can be understood to be part of an instructional package that contributed to increases in learning based on objective skills measures although it cannot be demonstrated to be the direct or exclusive cause of them.

5.3.3 ECE Self-Reflection

The self-reflection responses for the ECE course mirrored those for the CHEG course with one exception. All of the ECE students felt that the MR lab slowed them down. Approximately a third attributed this to needing to adjust to use of the equipment or technical difficulties like being disconnected during their lab and having to restart the system. It is also possible that the nature of the experiment or representation of the digital elements to be manipulated occurring at a smaller or larger than optimal scale contributed to slow downs. Further investigation by the project team will be required to understand this perception communicated by the students.

6. Limitations

There are several limitations that apply to the research. First, the MR module was enacted in one section of one course in each discipline. This had two primary impacts, limiting the scope of the investigation to two class sections, one per specialization, rather than multiple sections in each discipline and resulting in a small sample. While desirable, comparison of skills and self-assessment outcomes to those for non-experimental sections of the course offered in parallel was not possible as PVAMU does not have sufficient enrollment in the two disciplines to support multiple course sections in a semester. The small sample size reduced statistical power for analysis and made comparison of student outcomes to prior sections of the course impractical until a larger cumulative sample can be compiled over several semesters. There was also limited diversity in the population and sample as the courses were taught at an HBCU which has an overall population with 83.0% of students identifying as African American, 2.0% Asian, 0.1% Hawaiian/Pacific Islander, 8.7% Hispanic, 0.2% Native American/Alaska Native, 1.6% white, 1.6% multi-racial, 2.1%, international students, and 0.3% categorized as unknown. Comparisons of outcomes for males and females or by racial identity were not possible due the small counts in nearly all categories. And like much educational research, a direct and exclusive causation effect could not be established although there were strong indications of contributions to learning and skill development.

7. Discussion and Conclusions

As an initial and limited study, conclusions drawn must be viewed as tentative and in need of verification. Yet, the results from one semester of implementation are encouraging. Statistically significant increases in levels of understanding, for student pre- and post-instruction self-reports, were found. These were highly significant and universal for the constructs directly relevant to MR module content in the CHEG course. While all means increased with 15 of 16 standard deviations decreasing pre- to post-instruction for the ECE course, only one difference was found to be significant. As noted above, these outcomes were impacted by small samples, as few as 10 students, that limited statistical power and ECE students being confident pre-instruction with just under 50% of the ratings of understanding in the upper quintile of the scale. This limited the scope of possible increases in ratings and potential for changes to be found significant. However, the skills tests, objective measures of specific calculations, definitions, and descriptions, demonstrated statistically significant differences for both courses pre- to post-instruction. The combination of significant advancement in self-reported understanding and on skills tests is a strong indication of efficacy of the instruction provided. It is not possible, though, to link these results directly or exclusively to the MR activity; but it is possible to assert contribution toward the effects noted. The responses to the short answer, self-reflection questions submitted by participating students confirm this as they noted the process was engaging ("fun," "cool," "wonderful"), a good and helpful replication of real-world structures, patterns, and processes, effective for accomplishing the lab procedures, and beneficial for their learning.

Review of the literature caused the project team to select mixed reality as an immersive technology capable of supporting knowledge and skill acquisition, aligning with learning preferences of 21st century students, providing permanent but adaptable settings with real-world manipulable properties, safely expanding potentials beyond those of real-world settings, facilitating interactive learning, transcending some practical limits, and providing learning and creative opportunities to faculty. Data reported herein, supports the conclusion that these occurred. The preceding paragraph summarizes data supporting efficacy for knowledge and skill acquisition. Short, written responses from students support the conclusion that MR application aligned with their learning preferences while realistically mimicking real-world equipment and processes. The same set of responses provided evidence of interactive learning achieved through collaboration and problem-solving in group processes completed exclusively in a MR setting. Several practical limits were also overcome. For example, one of the items of equipment reproduced as a digital twin is large and takes up a great deal of space in a physical lab. That limits the number of stations that can be made available as well as the number of students who can have access to the equipment and the amount of time they can have access. None of these limits existed in the digital environment. Faculty discussion in project meetings, not detailed in this paper, demonstrated substantial learning and creativity. A development process, involving digital recreation of a variety of forms of physical equipment and natural processes plus appropriate positioning of these in an existing curriculum, had to be completed. Hundreds of hours were dedicated to research, discussion, design, story boarding, programming, testing, and refining all of which involved learning about and in an MR setting while employing creativity at every step.

As noted above, these outcomes should not be seen as confirmed or assured if the processes are reproduced. The initial findings suggest that the intended purposes may be realized but additional use of the MR assets in courses at Prairie View A&M University will be necessary to establish a strong case for efficacy. In addition, the results reported should not be seen as support for haphazard or random adoption of MR content. The materials deployed were produced in collaboration with a company specializing in MR, for a specific set of predefined purposes, by a team of professional educators. The project team believes that deliberate, specific, professional level planning and design is necessary to produce high quality, helpful MR content to support engineering education.

Several unexpected outcomes occurred. These were related to the equipment employed. Some students did not find the Hololens headsets comfortable. Many experienced headaches and some nausea from extended use of the headsets. These outcomes were unanticipated. Further investigation will be necessary to determine whether there was an aspect of the implementation that contributed to these unpleasant side effects, like the color, intensity, or pattern of the background of the projection as suggested by some students. It may also be necessary to provide an alternative approach to the MR lab for parties who experience some health issues like motion sickness.

8. Next Steps

Two years of NSF funding remain for the project. In that time, the team plans to deploy the MR assets already developed in other courses and to replicate the patterns reported in this paper in the same courses. This will provide a broad and multi-instance database including a much wider audience across multiple years. These processes are necessary to provide the scope of evidence necessary for demonstration of efficacy. They will also make it possible to gather data sufficient to address the three research purposes not discussed in this presentation.

The project team will consider different ways the equipment already replicated as digital twins can be deployed in instruction. This may involve creation of new instructional modules or different applications for the existing modules. They will also discuss and explore with their peers what other core content lab equipment might be replicated as multi-function digital twins.

Continued evidence of efficacy as an instructional tool will bolster an argument for continued use. In anticipation and support of that, the project team will share opportunities to use the MR materials with institutional colleagues and administrators. Simultaneously, they will continue to employ the products of the project described in this paper in CHEG and ECE instruction for which they are responsible. They will also continue to publicize outcomes from their work in hopes of expanding interest in MR as an instructional tool and adding to what is known about its impacts and benefits.

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