MIXED REALITY IN CHEMICAL ENGINEERING EDUCATION – A PROOF OF CONCEPT

Keisha C.A. Antoine, Lealon L. Martin, and Jorge F. Gabitto
Prairie View A&M University • Prairie View, TX 77446

INTRODUCTION

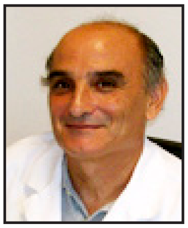
As a result of the lockdown imposed nationwide because of the COVID-19 pandemic, from an educational perspective, 2020 notoriously became the year of remote instruction and remote learning. The pandemic precipitated a need to introduce social distancing protocols to limit in-person contact or to avoid face-to-face interactions altogether. At the university level, students, faculty, and staff had to migrate quickly to online tools and platforms to administer course instruction in a matter of weeks. In essence, the COVID-19 pandemic introduced new behavioral norms that were not as conducive to effective instruction of some classes (e.g., laboratory courses) in comparison to more traditional instructional modes. For example, the senior labs at Prairie View A&M University (PVAMU) are administered in a team-based format, where three to five students work together and conduct experiments with the aim of producing a group report showcasing advanced technical analysis that would correlate their theoretical knowledge with newly gained practical experience. The structure of our lab courses lends itself to close, social interaction in almost every aspect of every class activity. However, social distancing and quarantine measures required innovative course design modifications to ensure that pandemic-related health and safety standards were met while minimizing disruption in the instructional learning process.

In preparation for our senior chemical engineering laboratory courses, we created instructional videos showing students how to run the experiment and separate videos giving information about the equipment itself – its purpose, how it functions, and a description of how data is collected. We also supplied the students with a composite of experimental data from previous student reports or from data that we, the instructors, collected ourselves. The students were then instructed to write the lab report based on these inputs. While effective, the major shortcoming was the limited context that this method provided because the students did not have a "hands-on" experience. First-person immersive experiences are crucial to developing deeper knowledge and understanding.[1] The lack of a first-person immersive experience was an instructional limitation, and lack of videography expertise also made this method of providing remote instruction difficult to scale to other experiments or other engineering labs. It has been reported that underrepresented minority students have a learning preference for STEM courses that incorporate hands-on experiences and content that connect to their communities over a strictly theoretical approach.[2]

Keisha C.A. Antoine, *PhD, PE obtained a BS in Chemical Engineering in 2001 and a M Eng and PhD in Materials Science & Engineering in 2004 and 2007, respectively from Lehigh University. She is a registered professional engineer in the state of Texas and is a lecturer in the Chemical Engineering Department at Prairie View A&M University. Her research interests are interdisciplinary in nature involving the use of immersive technologies in engineering education.*

Lealon L. Martin, *PhD, JD is a faculty member in the Chemical Engineering Department at Prairie View A&M University. He received his BS degree in Chemical Engineering from Tuskegee University, and a PhD in Chemical Engineering at UCLA. He is also a licensed attorney and a member of the State Bar of Texas. Dr. Martin's primary research interest lies in the synthesis and reconstruction of metabolic networks using state space optimization-based approaches.*

Jorge F. Gabitto, *PhD obtained a BSc and a ScD.in Chemical Engineering from the University of Buenos Aires, Argentina. He joined the chemical engineering department at Prairie View A&M University in Fall 1991. Dr. Gabitto has published more than 60 scientific articles in refereed journals. He has carried out more than 20 research projects. He has been a faculty intern and external research collaborator at Oak Ridge National Laboratory from 1999 until the present.*



Additionally, as educators at one of the US's Historically Black Colleges and Universities (HBCUs), we were interested to pursue the investigation of mixed reality (MR) technology for educational instruction to be used as a tool to reverse the trend of low representation of African Americans among STEM program graduates[3, 4] and in STEM jobs after graduation.

Interestingly, Gao et al.,[5] in their implementation of remote instruction for unit operations labs, posited that the students missed the in-person experience where they could interact directly with the equipment. This lack of in-person experience was regarded as a missed opportunity that would allow the students the prospect to face and solve unplanned problems. This team observed that an essential part of the lab class that enabled confidence-building or the willingness to tackle unexpected challenges was not reproduced as effectively compared to when the students were in a physical lab. "Confidence-building" can be likened to tacit learning, that is, knowledge that has moved from conscious (know-what) to the subconscious (know-how) level.[1]

While this paper's focus is on the proof of concept engineering MR module, it is beneficial to mention that in the PVAMU Chemical Engineering Department, laboratory courses are mapped to the student learning outcomes of the Engineering Accreditation Commission (EAC) of the Accreditation Board for Engineering and Technology (ABET):[6]

- ABET EAC Student Outcome 3 – an ability to communicate effectively with a range of audiences
- ABET EAC Student Outcome 5 – an ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives
- ABET EAC Student Outcome 6 – an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions.

We have historically assessed all three student outcomes by assessing the written reports and oral presentations of the student teams, and expect to maintain this method of assessment for MR labs.

Work by Telesca et al.[7] has discussed that US students' performance in science assessments is below that of other industrialized nations chiefly because the majority of US high school students lack the requisite written communication skills. This is because the typical writing tasks that STEM high school students are assigned fall into the "restricted writing"[7] category, such as note-taking, short, written answers, and fill-in-the-blank worksheets. At the university level, we require extended written composition, where students need to write scientific arguments supporting theories with evidence. It is difficult to address this lack at the senior university level after years of conditioning. However, we feel that oral and written communication are directly impacted by a student's inherent understanding of the subject material, understanding that they can gain through thoughtful implementation of labs.[8] Understanding leads to clarity of thinking; this means that seeing the relevance of abstract concepts by "experiencing" them can increase understanding and consequently student competence and confidence,[1, 9] thus improving their ability to communicate what they learn.

One may question how the written reports and oral presentations could be used to assess teamwork. The authors have observed that the reports are an indicator of teamwork dynamics, as noted by the following:

1. Not all students in a group have the same degree of involvement or participation during the lab exercise, and this is reflected in the final work product "the report." While student performance in data acquisition is satisfactory, data analysis is deficient, as can be seen in the Discussion section. This issue leads to incorrect conclusions.
2. There is oftentimes poor communication between group members and poor project and time management among group members. We receive reports after the due date or reports that are poorly written.
3. The reports demonstrate poor continuity from section to section because they are an obvious patchwork of the contributions of several individuals who have not discussed the experiment, its relevance, nor its conclusion.

A factor that has often been cited by students as a barrier to effective teamwork is the requirement that students be physically present in the same location after the lab experiment for data analysis, interpretation, and final report writing. An additional challenge to in-person meetings was the requirement for social distancing in the COVID-19 environment. While not employed in Gao et al.'s implementation,[5] the team did mention in its concluding remarks that virtual reality (VR) could be used as a different modality of instruction for virtual (i.e., remote) learning. Giving students access to virtual reality/mixed reality (VR/MR) tools will immediately address the physical location requirements by allowing remote, yet immersed, interaction.

We believe that MR can directly and immediately improve the ability of our students to make insightful connections between theory and practice [1, 9] and thus would directly improve ABET EAC Student Outcome 6 – experimental design and analysis. Engineering as a whole, and chemical engineering in particular, 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 arrive at a deliberate, ordered process. As instructors, we perceive this difficulty in making the "jump" from theory to application as a lack of critical thinking skills.

Thus, while it is the COVID-19 pandemic that provided the motivation for our team to embark on an investigation of a learning tool that can be employed for remote instruction in a laboratory context, we are beginning to see that MR technology can provide immersive learning experiences that can improve ABET student learning outcomes. While it is possible to assess student learning through the existing ABET framework, due to the limited focus of this work, which was to develop a working MR proof of concept for a fluid mechanics lab, the focus of this paper will be on providing a summary of our experience. The assessment of the effectiveness of MR technology for engineering education will be left to another time.

ABOUT MIXED REALITY

While ZOOM®, Google Meet® and other virtual meeting platforms have existed for some time and more institutions offered remote, online learning opportunities, the COVID-19 pandemic was the trigger that culminated in the wholescale transfer of the world's population into e-learning. E-learning can use a variety of electronic media, including text, streaming video, document sharing software, etc., to broaden the learning environment for students. With the widespread availability of smart devices that are mobile and interconnected, the learning frontier has been extended even further. Immersive technologies such as VR and MR have lately been increasingly receiving attention as instruments of this frontier extension.

VR and MR exist on what is known as the virtuality-reality continuum (Figure 1), whereby the learner is transported to a digital, synthesized environment. This may totally exclude the physical world (as in VR) or can keep the learner in the physical world, allowing the user to interact with digital elements that are superimposed onto physical environments and real-world objects (MR). While mixed reality encompasses the entire spectrum, when we use the term mixed reality (MR), it is commonly understood to mean augmented reality (AR), where the 3D digital elements are superimposed on the real world. The user is still aware of the physical environment – the physical environment does not affect the digital elements – and can interact quite separately with the physical environment and with the digital element(s). The digital element(s) can only be manipulated through the user's hand gestures, voice, and gaze.

In both MR and VR, the users interact with these 3D digital elements through headsets rather than via a screen, thus providing a truly immersive experience. For our proof of concept (POC), we chose to go with MR instead of VR because we felt that it more easily enabled direct interaction amongst learners by facilitating instinctual interaction with real 3D visuals in a real and contextually relevant environment. In 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 that can provide different points of view that thus far had been inaccessible to both learners (students) and instructors.

With MR, a student can directly interact with abstract concepts, engage with variables in engineering equations, manipulate them, and get 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, students engage with visual, auditory, motor, and spatial relations elements of the environment, immersing them in the content. By utilizing MR, we can incorporate inherently immersive experiences and circumvent practical limitations such as the expense to run an actual physical

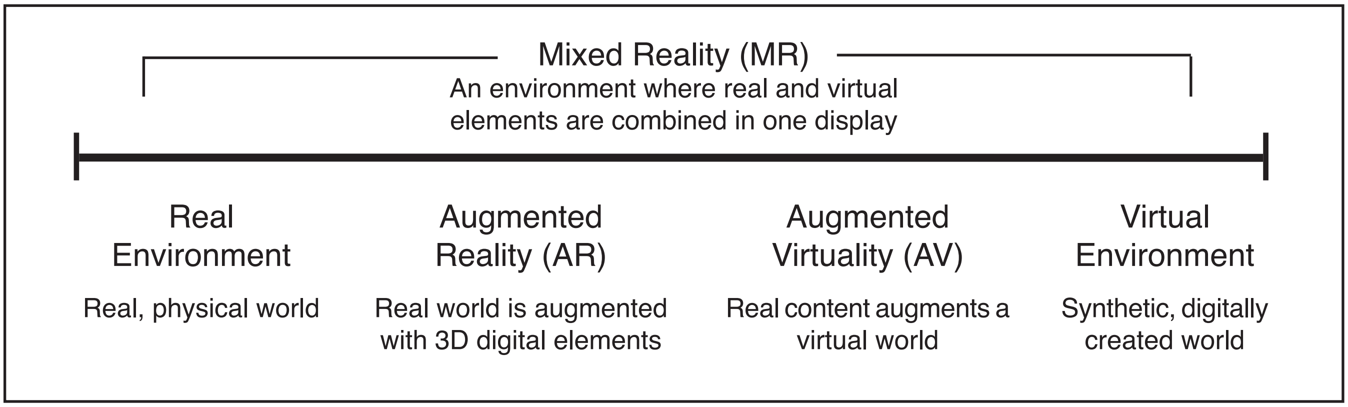


Figure 1. *The virtuality-reality continuum (after Milgram and Kishino [10])*

experience (that can greatly exceed the not-inconsequential cost of the MR headset and technology implementation), logistics, scale (large or small) and risk. For a well-constructed, virtual environment, the setting itself contributes to bridging the gap between know-what to know-how in a realistic, accurate, and safe environment.[11]

It should be mentioned that MR has been used in anatomy courses for training medical students.[12] With this technology, one can now see holographic representations of the human body and can rotate the body in different directions to reveal the different organs to get the best view of them. Additionally, the students can also engage with the instructor from their respective locations, which can be thousands of miles away. This reference [12] also revealed that an unintended benefit was that the technology's ability to represent an organ like the brain in 3D improved the instructor's spatial understanding of the organ (even with the instructor's extensive experience in looking at datasets of brain MRIs). However, despite the benefits of the use of this technology, it has not found widespread application in education because of cost and an inherent barrier to adopting a new technology. In the following content, we will demonstrate how MR can be used to carry out a chemical engineering unit operations experiment.

PROOF OF CONCEPT DEMONSTRATION

We used internal Prairie View A&M University funds that were awarded by the Office of the Vice President for Research & Innovation to develop a working POC of a classical fluid mechanics experiment: the investigation of friction effects in pipe flow by observing pressure drop as a function of volumetric flowrate through a straight run of pipe. This relationship depends on the pipe characteristics: surface roughness of the interior of the pipe, internal diameter and length, and the fluid properties – namely viscosity and density. These parameters are related to each other through the dimensionless Reynolds number. Typically, students performing this lab experiment in groups and in a traditional face-to-face setting would turn on a pump, manipulate valves to change volumetric flow rates, and read the resultant pressures at the beginning and end of the pipe run. Figure 2 is an image of the existing equipment that is used in the chemical engineering unit operations lab to perform these types of experiments.

The friction in pipe flow experiment serves as a suitable pilot for the following reasons. First, it fell under the subject matter of fluid mechanics, which is a mature and well understood field. This fact would mitigate the possibility of any uncharacteristic or inexplicable behavior. Next, this lab experiment is conducted at most institutions where chemical engineering is offered as a field of study. By implementing the pilot study using a typical and ubiquitous experiment, the investigators could pre-emptively address a potential resistance to new discoveries arising from this study by our peers at other institutions.

***Figure 2.** Edibon AFT-B Fluid Flow in Pipes equipment that is used at PVAMU Chemical Engineering Laboratory.*

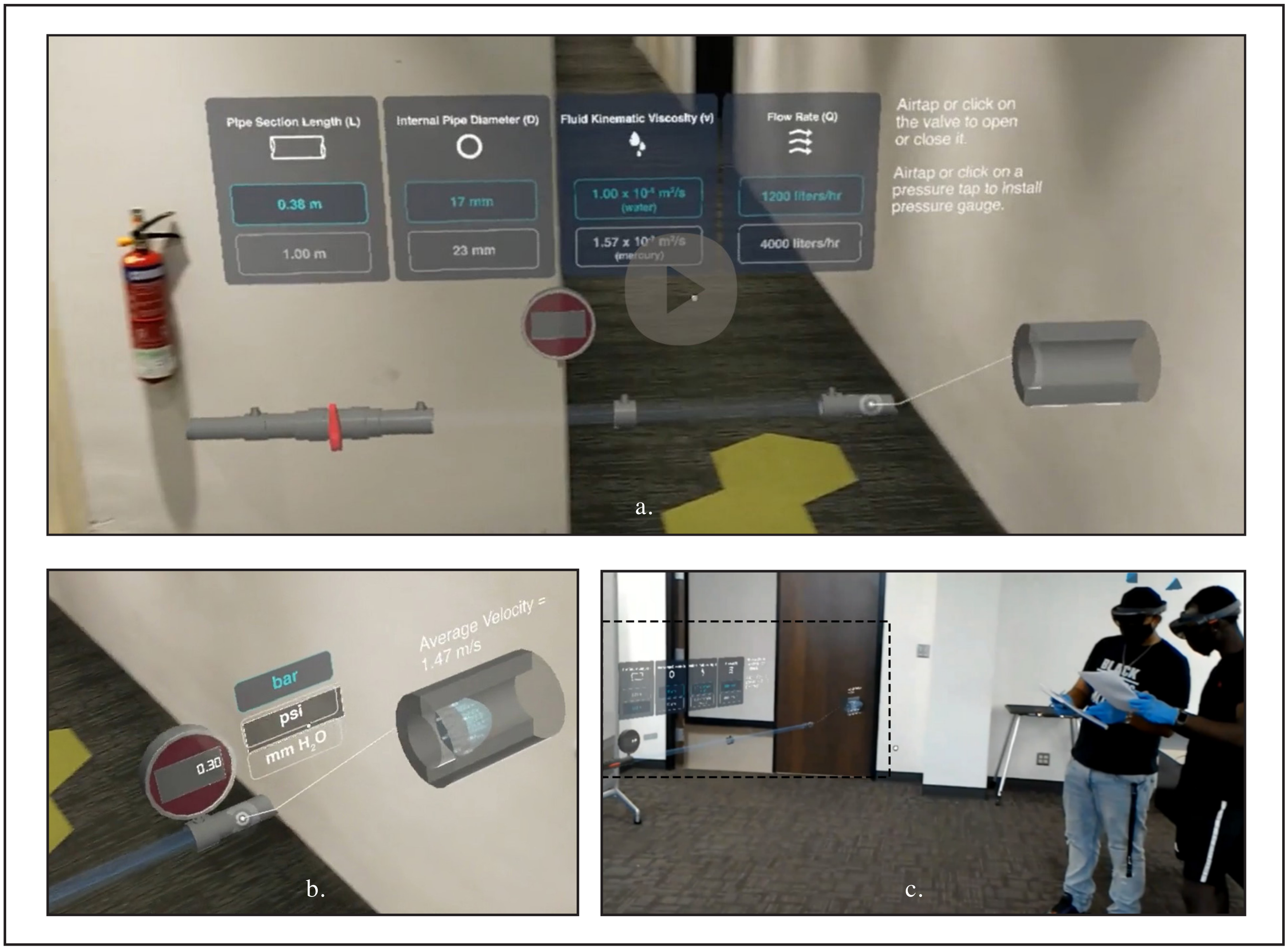
A recruitment email message was sent to the seniors through the department administrator requesting student volunteers. Our target population was senior students since they would have completed fluid mechanics coursework. In this way, we mirrored delivery of chemical engineering instruction at PVAMU, where the students perform the lab only after having successfully gone through and passed the theoretical aspects of the curriculum. Two students volunteered and tested the POC on two separate occasions. While no incentive was advertised, a $25 Dominos® gift card was given to each student volunteer at the end of the second test.

Having no in-house developer capability, we procured the services of the developer, Serl.io, to create a working POC of the MR 3D digital element and to allow the user to perform experiments with simulated data. The POC was designed around the Gen 1 Microsoft HoloLens® headset and was conducted in the Chemical Engineering Department at Prairie View A&M University.

The Microsoft HoloLens is the world's first fully untethered holographic computer. It is a see-through, mixed reality headset featuring cutting-edge optics and sensors to deliver 3D assets (holograms) pinned to the real, physical world around the user, allowing for an immersive experience. The headset is untethered, thereby allowing for more natural interaction with a mixed reality environment when compared to interaction through a screen and cursor.

The POC sessions described here used the Gen 1 headset. The user's field of view was 34 degrees, and the computing power of the Gen 1 headset restricted its user to a small number of hand gestures – air taps and basic palm moves – because it lacked depth perception between the hands and the 3D asset. The Gen 1 headset did not track the eyes. It is also front-heavy, as it stores most of its components there. This balance causes the weight to be applied to the wearer's nose and front of the head, causing neck strain. The newer HoloLens Gen 2 version of the headset has addressed these issues. In the Gen 2 headset, the user's field of view is 52 degrees and the headset has the ability to perceive depth, and is therefore better at tracking the hands and allowing the user to grab and move the 3D asset. The Gen 2 headset also has the ability for eye tracking and gaze tracking. By placing the components throughout the sides and back of the headset, the weight in the Gen 2 version is more evenly distributed. Voice commands are available on both generations of the device, with Gen 2 having advanced voice tracking features. We did not utilize the voice input features in our POC. While in future work we plan to utilize the Gen 2 headset with its enhanced features, it is important to reiterate that the Gen 1 headset was used for the POC.

The sessions conducted to demonstrate the POC were screencast to Zoom®, and the Zoom sessions were recorded. As shown in Figure 3, we created an immersive and socially interactive experience where the student volunteers, through their hand gestures, were able to "touch" the menu to vary any of the parameters and record the resultant pressures along the run of pipe. The 3D pipe was to scale, making it large enough to give the students some perspective of scale and allowing the students to move around and interact with it as it was "anchored" to a given location in space. In this POC, the users were able to turn on the flow by touching the digital valve and then manipulate the flow rate through the digital menu. Through the digital menu, the students could also vary the pipe diameter, pipe length, fluid viscosity, and density. The POC had neither sound nor haptic feedback. Future development can incorporate these beneficial features to add some realism to the session.



Airtap or click on the valve to open or close it.

Airtap or click on a pressure tap to install pressure gauge.

Figure 3. *Screen captures showing what the students actually see through the Microsoft HoloLens. (a) A rendering of the proof of concept (POC) with readouts showing pipe length, pipe diameter, fluid viscosity, and flow rate. Also included are the pressure gauge, valve, and instructions for how to use hand gestures to vary the parameters. (b) The velocity profile rendering in the POC. (c) Two senior-level students using MR in a physically co-located environment. The students are wearing the Microsoft HoloLens that allow them to manupulate the virtual experimental display (shown in the far left of the image inside the dashed box). They are also reading from the papers held in their hands.*

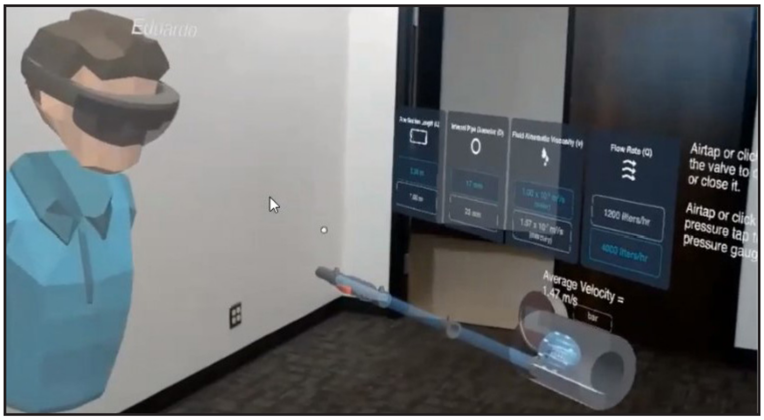


Figure 4. *An example of MR used to facilitate collaborative learning between two students even though they are not physically co-located. The image is taken from the perspective of the student who is located in the lab. The avatar (left) represents the second student who is not physically present in the same space as the first student. Both students use the Microsoft Hololens technology to view and interact with the pipe simulation digital element (right) simultaneously with no time lag.*

Pressure reading results obtained by the students were modeled results that were generated by the authors using a combination of actual empirical data from in-house equipment (Figure 2) and fluid mechanics equations. A limitation of this approach is that we had a fixed number of inputs and a resulting fixed number of outputs. The inputs included the fluid (2 count), pipe diameter (2 count), pipe length (2 count) and flow rate (2 count) for a total of 16 different input combinations to yield 16 upstream and 16 downstream pressure values as outputs. A stochastic approach that can provide live, dynamic data could be considered in future iterations. For the POC, water and mercury were the fluids investigated, enabling the students to gain understanding of different flow regimes – turbulent, transitional and laminar – by showcasing renderings of the velocity profile to the students (Figure 3b).

In the physical lab, we can vary the pipe diameter and length by making use of multiple pipes (Figure 2); however, while it is possible to change the liquid, in practice we only experimented with water for safety concerns, storage, and other logistic reasons. From the data captured, the students would be able to proceed with different fluid mechanics calculations as they would in an in-person lab experiment: calculation of Reynolds number, pressure drop, friction factor. The ability of MR to facilitate changes to experimental conditions quickly, completely, and without safety, contamination, and logistic issues is a distinct advantage.

The POC also allowed us to demonstrate that this technology could be used to implement remote learning (Figure 4) as the student volunteers operated on the same 3D digital pipe through internet connectivity even though they were in different physical locations. The remote student is observed as an avatar. The interaction is dynamic and instantaneous, and the students were able to collaborate with no time lag. This opens the possibility for our institution to provide remote collaboration as an option to students. As availability to the learning exercise is no longer subject to a weekly class schedule, both synchronous and asynchronous modes of learning can be accessed, thus addressing the broader impact of providing flexibility of access for students while preserving an immersive and socially interactive experience. Asynchronous access will also help address obstacles to teamwork by eliminating the necessity of having to work in the same physical location during lab time.

It should be pointed out that the benefits that we purport in our POC are in accordance with many of the benefits highlighted by Falconer and Hendren[13] in their paper on virtual labs. In their offerings, they have made available simulated labs on a computer that can be accessed by the student for self-study purposes.[13, 14] These labs are offered as modules that students can access at will and allow the students to learn complex chemical engineering themes. These virtual labs are different from virtual reality or mixed reality offerings in that they are not immersive, as the students interact with the modules through a computer monitor.

INITIAL STUDENT FEEDBACK

The POC was tested with two senior-level student volunteers. An experiment was devised to test the POC, which consisted of 3D digital pipe with a digital menu. The students conducted an experiment where they were tasked to vary the flowrate and measure the upstream and downstream pressures along the run of pipe for a given pipe inner diameter and pipe length, which are both student-selected variables. The students were able to change the fluid under test. A self-reflection survey was given to the students to complete immediately after trial of the POC. Below are the questions and actual 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 an experiment.

   Student 1: Easy to use, wish there was wider field of vision, pop up windows with a table of density or table implementing bar. It would help to know if the flow was laminar or turbulent.

   Student 2: Easy to use depending on program. Decently comfortable.

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 the data?

   Student 1: Definitely speed up the process very much. It helps you visually realize what is going on inside the piping system.

   Student 2: Acquiring data was faster because it was calculated by the software. There was less room for error. If error occurred, it could be fixed from on the software than having to fix physical lab equipment.

3. Is there any difference in the way you took the data compared to how you would do it in a physical lab?

   Student 1: Almost the same actually. I would prefer the virtual lab.

   Student 2: No. Great for lab. If not enough lab equipment, great substitute.

4. 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?

      Student 1: It blew up a simple concept of unit operations and made it very interactive and having the ability to see each team member's crusor [sic] *allowed for effective communication within the experiment as being able to jump in to point at something and assist when someone is lost.*

      Student 2: It was a great way to acquire data quickly. It was good to see the parameters change visually as we checked. Professors can see what students struggle with.

   b. An ability for social interaction?

      Student 1: No response from Student 1.

      Student 2: Great for teamwork. While (the rest of the response is illegible).

   c. The ability to interact remotely with team members?

      Student 1: Proffesor's [sic] *via Zoom were able to tap into visual through screen share to see live what was going on through the HoloLens.*

      Student 2: Professor recorded on Zoom. Great way to do online lecture.

5. Any other feedback that you would like to share?

   Student 1: I would add (?) a tip icon along the piping experiments to answer frequently ask questions of student's and thus go a step farther to add hints on what theorem to use (where?) and help student's [sic] *identify that (Bernoullis, Moody chart, etc….so they can calculate numbers more accurately.*

   Student 2: Being able to move the applications up and down could be good. Strain on the neck if you have to look down a lot. Casting device causes drain on eyes. If you can add a drop-down menu or pipe (illegible) that has helpful info (i.e., equations, concepts, parameters).

DISCUSSION

With a small sample size of two students, it was only possible to do a qualitative analysis of the results. The qualitative analysis is comprised of an evaluation of the initial student feedback and the authors' impressions. We can categorize the feedback into the following main themes: (1) ease of use for a thought-out and developed 3D virtual scenario, (2) user experience in using Microsoft HoloLens, (3) ability for social interaction, and (4) extending the use of implementation of the technology.

Ease of Use for a Thought-Out and Developed 3D Virtual Scenario

Both students entered the study with limited knowledge of the Microsoft HoloLens and had not had prior hands-on experience with it. They were provided verbal instructions in its use as it pertained to interacting with the 3D pipe simulation, the 3D menu, the 3D pressure sensor, and turning on and varying the simulated flow. The instruction portion took less than 15 minutes, and the students were able to complete the lab exercise relying on the written instructions and the discussion between themselves. We could see that the students consulted each other to check results. Both students reported that the program was easy to use. As instructors, we recognize that the ease-of-use stems from a virtual experimental setup that has been completely conceptualized, akin to a piece of equipment with all components assembled and in good working order. Typically, this is a lab that is carried out by a team of three to five students. A larger sample size would have allowed us to see whether we see the same dynamics as in a physical lab with two to three engaged students and the rest minimally engaged.

User Experience in Using the Microsoft HoloLens

Students reported that the headsets had decently comfortable ergonomics. Recall that the POC was performed with Gen 1 headsets, where its weight made it uncomfortable for extended use. The HoloLens has no handheld controllers and instead relies completely on hand tracking. For Gen 1 headsets, there are a limited number of points or articulations per hand such as basic gesture-based finger taps and basic hand moves. These hand gestures could take some time to get accustomed to, but after an adjustment period, it is apparent that these gestures become intuitive to the users. One of the students commented positively about the wide field of view. In later verbal discussions, the student who wished for a wider field of vision clarified that he would have appreciated using an instrument where he could minimize how much he had to turn his head when focusing on the 3D virtual pipe to see the "big picture." This student also mentioned that it could be beneficial to have the capability to zoom in on certain parts of the 3D object by gesturing as opposed to having to turn his head and walk up to the object to have a close-up view to see the whole diagram or system being shown.

Ability for Social Interaction

Students were able to interact socially during the sessions both when they were in the same location and when they were in different locations from each other. When not physically co-located, the student could interact with his counterpart in real time with no lag. The counterpart's presence and activity were marked by the observance of his avatar. The social interaction allowed for the students to share and point out to other scenario participants – the instructor, counterpart – his particular area of interest in the lab. It was easier to revisit different aspects of the lab so that a student can keep up or get caught up (in cases of momentary lapses in attention) with the pace of the activities. The ability for social interaction is helped by ease of use as discussed earlier.

Extending the Use of Implementation of the Technology

In performing the lab exercise, the students were able to recommend areas of improvement. In a physical lab, it is not practical to add tips to every piece of equipment. In an MR session, tips for performing the experiment or linking to the relevant areas of theory can easily be added in the form of 3D menus that can be accessed and put away, as needed.

CONCLUSIONS

It can be difficult to translate theoretical knowledge into practical application. While not reality, through immersive technologies such as VR and MR, we can facilitate theoretical to practical knowledge transfer, i.e., know-what to know-how, in a safe, situationally relevant environment. Because MR can allow us the ability to access scenarios that were previously out of reach because of cost, safety, or logistics, there is the added benefit that real-world consequences do not exist allowing learners to suspend disbelief and be more confident in risk taking and enabling learners to understand abstract concepts.

The mixed reality POC implemented enabled the following beneficial pedagogical aspects: (1) creation of a practical, situationally relevant immersive and socially interactive experience and (2) remote engagement, while preserving immersive and social features. Initial student feedback suggests that it is worthwhile to pursue MR technology as a tool for virtual labs. From the instructional team perspective, we observed that MR could allow for synchronous and asynchronous instruction modes. Students can interact with one another through guided (with the instructor present on an MR session) and unguided sessions. This provides an environment where students can step out and make meaning for themselves, directly tapping into the preferred means of learning for African-American students. By addressing their learning preferences, it is hoped that we can reverse the trend of low representation of African American students among STEM program graduates and in STEM jobs after graduation. Serendipitously, we observed that it was possible to implement MR as an instructional tool, such as by having the instructor screen cast his/her MR session over a Zoom meeting or webinar. As we progress with the implementation of MR, we can envisage scenarios where the students themselves become content creators.

A missing component in the MR POC was the ability to implement use cases for dynamic scenarios that have some element of randomness, i.e., fluctuations or user or measurement error. As mentioned earlier, for the specific use case of fluid flow through pipes, the POC was limited to a fixed number of inputs and resulting outputs. To address this would require connecting the MR session to a computational fluid dynamics program or some other stochastic tool that can extend the input bounds, introduce randomness, and account for the physics occurring to provide realistic results. Additionally, adding sound and haptic feedback capability could help improve the realism of these lab sessions or other use cases, making them more immersive. These features can help justify the cost of implementation of MR technology in the chemical engineering curriculum.

As presented earlier, we utilized an outside developer, Serl.io, to develop the 3D pipe and menu, which were connected to modeled inputs and resulting outputs. Just as there are an infinite number of experiments that one can perform in a lab, there are an infinite number of lab use cases that can be created. Thinking of long-term feasibility, we would need to train in-house personnel in the use of MR technology, i.e., the use of HoloLens headsets as well as training on use of developer software to create content. Widespread adoption of MR in education would require that instructors become as familiar with developer tools as they are with learning management systems.

Finally, it is exciting to discover new tools that can be repurposed for the field of education. MR has a lot of promise to revolutionize how we learn. It extends the e-learning frontier, making it possible to access synchronous and asynchronous instruction modes. It allows more avenues for learners to take risks because it provides a safe environment where they can suspend disbelief, exceed physical bounds, and break natural laws of physics. In spite of these benefits, there has still not been widespread adoption of this technology in education, neither in K-12 nor in higher education. To our knowledge, MR has not been implemented in engineering education. The cost of the headsets is still a barrier to adoption. As described in the preceding paragraph, personnel need training. Also, there is just a natural hesitancy on the part of the instructors and the learners to try something new. While we recognize that there is still some way to go where we see MR's ubiquitous use in schools, there is comfort that these barriers are being tackled as more people become aware of MR and become more open to its use.

REFERENCES

1. Bonasio A (2019) Immersive experiences in education: New places and spaces for learning. Microsoft Whitepaper. https://documents.pub/document/immersive-experiences-in-education-immesive-epeiences-in-educatin-1-about-the-author.html?page=2 accessed Oct. 24, 2023.
2. Rainey K, Dancy M, Mickelson R, Stearns E, and Moller S (2019) A descriptive study of race and gender differences in how instructional style and perceived professor care influence decisions to major in STEM. *International Journal of STEM Education*. 6(6). https://doi.org/10.1186/s40594-019-0159-2. accessed Oct. 24, 2023.
3. Newsome M (2021) Even as colleges pledge to improve, share of engineering and math graduates who are Black declines. *The Hechinger Report*. https://hechingerreport.org/even-as-colleges-pledge-to-improve-share-of-engineering-graduates-who-are-black-declines/ accessed Oct.24, 2023
4. Smart A (2020) After years of gains, Black STEM representation is falling. Why?, *Undark*. https://undark.org/2020/09/11/after-years-of-gains-black-stem-representation-is-falling-why/ accessed Oct. 24, 2023.
5. Gao J, Crossley SP, Nollert MU, Lobban LL, and Papavassiliou DV (2021) Online teaching of a lab course amid a pandemic – A challenge and an opportunity. *Chemical Engineering Education*. 55(2): 76-84. https://doi.org/10.18260/2-1-370.660-124795 accessed Oct. 24, 2023.
6. Criteria for Accrediting Engineering Programs, 2022 – 2023 https://www.abet.org/accreditation/accreditation-criteria/criteria-for-accrediting-engineering-programs-2022-2023/ accessed Oct. 24, 2023.
7. Telesca L, Ehren B J, Hahs-Vaughn D L, Zygouris-Coe V "Vicky" I, and Pak-Hin Kong A (2020) The effect of metalinguistic sentence combining on eighth-grade students' understanding and written expression of comparison and contrast in science. *Journal of Speech, Language & Hearing Research*. 63(9): 3068–3083. https://doi.org/10.1044/2020_JSLHR-19-00086 accessed Oct. 24, 2023.
8. Feisel LD and Rosa AJ (2005) The role of the laboratory in undergraduate engineering education. *Journal of Engineering Education*. 94(1): 121-130. https://doi.org/10.1002/j.2168-9830.2005.tb00833.x.
9. Antonova A (2013) Virtual Worlds in the Context of Competence Development and Learning. In S. D'Agustino (Ed.). *Immersive Environments, Augmented Realities, and Virtual Worlds* (pp. 194-208). Hershey, Pennsylvania: Information Science Reference (an imprint of IGI Global).
10. Milgram P and Kishino F (1994) A taxonomy of mixed reality visual displays. *IEICE Transactions on Information and Systems*. 77: 1321–1329. https://search.ieice.org/bin/summary.php?id=e77-d_12_1321 accessed Oct. 24, 2023.
11. Shaoze Wu, Lei Hou, Guomin (Kevin) Zhang, and Haosen Chen (2022) Real-time mixed reality-based visual warning for construction workforce safety. *Automation in Construction*. 139: 104252. https://doi.org/10.1016/j.autcon.2022.104252 accessed Oct. 24, 2023.
12. Case Western Reserve University (2015) *Case Western Reserve, Cleveland Clinic collaborate with Microsoft on Earth-shattering mixed-reality technology for Education*. Case Western Reserve University – Hololens. https://case.edu/hololens/ accessed Oct. 24, 2023.
13. Falconer J and Hendren N (2021) Virtual catalytic reactor laboratory. *Chemical Engineering Education*. 55(3): 183-188. https://doi.org/10.18260/2-1-370.660-126043.
14. Falconer JL, Bourland KR, deGrazia J, and Medlin M (2020) Teaching tip: Interactive self-study modules for chemical engineering. *Chemical Engineering Education*. 54(3): 171. https://journals.flvc.org/cee/article/view/115574 accessed on October 24, 2023.❑