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Creating Mixed Reality Lab Modules for a Chemical Engineering Fluid Mechanics Lab – Work in Progress

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Abstract

A main outcome of the COVID-19 pandemic was the recognition that there is a need for educational technologies that provide a first-person, immersive experience to allow for effective instruction for chemical engineering laboratory courses, which are traditionally offered in person. In the aftermath of the pandemic, both educators and students alike appreciate the benefit of remote learning, whether synchronous or asynchronous. Our research team has decided upon mixed reality technology as the option that can provide the above-listed features, in addition to giving student participants the opportunity to collaborate.

Mixed reality (MR) is a technology where 3D holograms are superimposed onto a physical environment. A first-person, immersive experience is achieved through the user accessing these 3D holograms through a head-mounted display. In MR, the user still has full cognition of the physical environment because the user can see through the headset. This paper will walk through the design steps undertaken by the team to develop MR laboratory modules for chemical engineering based on a digital twin of the fluid flow through pipes equipment that is used for undergraduate instruction. This work follows on from the proof-of-concept discussed in a previous publication and includes discussion of increased functionality, and opportunities for tracking student use to evaluate if MR is an enhancement for student learning in an engineering context.

Keywords: formative assessment, active learning, constructivism, mixed reality, virtual reality, student-centered instruction, educational technology, remote learning

Conceptual Overview

This paper is one of several describing the ongoing development and results obtained for of an NSF-funded project to develop mixed reality (MR) laboratory modules for Chemical Engineering (CHEG) and Electrical & Computer Engineering (ECE) disciplines at Prairie View A&M University (PVAMU). The MR modules provide first-person, immersive experiences to students. We posit that these experiences provide a measure of practicality to abstract concepts, thereby enhancing learning outcomes. Research has shown that students demonstrate better learning outcomes if their learning encompasses a strong experiential component (Bonasio, Microsoft Whitepaper, 2019). The approach proposed addresses that and two items from the list of Grand Challenges the National Academy of Engineering (NAE) has identified as areas for emphasis; they are "Advanced Personalized Learning" and "Enhance Virtual Reality" (NAE Grand Challenges, 2022).

We had described the initial proof-of-concept work in a previous publication (Antoine et al., 2024). As before, we contracted the developer services of Serl.io, a Microsoft Mixed Reality Partner, to develop the mixed reality environment (or digital twin). The modules developed run on Microsoft HoloLens2 headsets. The HoloLens 2 is an ergonomic, untethered, self-contained holographic device that is finding increasing use in manufacturing, engineering and construction, healthcare, and education. Any context or environment can be reproduced or created with the equipment making it infinitely adaptable and able to be deployed in new contexts as they develop. It is the MR device of choice for this project because of its proliferation in the marketplace, its ability to generate and capture many kinds of data (gaze, gesture, position, orientation/location, speed of movement, etc.), its ability to record sessions and Serl.io's experience in developing apps using Microsoft HoloLens infrastructure. There is also voice connectivity among users in the same session. We used Serl.io's development expertise to create two digital twins, one for CHEG and one for ECE. The focus of this paper is the development of the CHEG digital twin. The ECE digital twin will be described in a separate paper.

Our project focus was on creating mixed reality environments where the students can have immersive experiences while encountering accurate outputs that correlate to their inputs. The output responses to inputs were governed by physical or empirical relationships. To enable realistic data output, the CHEG team provided expertise in fluid dynamics, numerical methods, pipeline networks, MATLAB, FORTRAN, logic structures, lab procedures and student learning outcomes. This information was provided to Serl.io, to create a digital twin of the piping network that was "smart" and dynamic. The inspiration for the digital twin was the Edibon AFT-B Fluid Flow in Pipes (Figure 1). Table 1 presents the comparison of the physical equipment, proof-of-concept and the Mixed Reality Labs. The CHEG MR digital twin has been expanded in scope over the proof-of-concept and provides extended capability over the physical equipment. One major addition is the inclusion of ten fluids (see Table 1).

Other benefits of the MR environment are: 1. Social interaction. It provides the ability for social interaction, thus facilitating teamwork. 2. Remote learning capability. The MR environment is being developed to enable remote learning where the students can interact with one another via their personalized avatars as in multi-player online games. 3. Practice opportunities. The MR environment was constructed to allow for single-player and multi-player modes and asynchronous access as well as immediate repetition of processes and/or extended use "experimenting" with different configurations and fluids. It is important to note that the scope of development did not include tools or interfaces to edit the software post development; any changes would require refactoring at the code level.

Figure 1. Edibon AFT-B Fluid Friction in Pipes Unit with hydraulics feed system (FME00/B).

Table 1. Comparison of list of inputs for the physical Edibon AFT-B equipment, Proof of Concept and Mixed Reality Modules.

Inputs	Edibon AFT-B	Proof of Concept	Mixed Reality Digital Twin
Fluids @ 20ºC	1 count – water	2 count – water, mercury	10 count – water, mercury, blood, ethylene glycol, ethanol, acetic acid, benzene, toluene, diesel, carbon tetrachloride
Pipe internal diameter	4 count	2 count	Variable (3 – 102 mm)
Pipe length	1 count	2 count	Variable (0.3 – 5.0 m)
Pipe roughness	2 count – rough, smooth	Not offered	Variable – choice of materials drawn tubing (brass, lead, glass, and the like [0.00152 mm], commercial steel or wrought iron [0.0457 mm], asphalted cast iron [0.122 mm], galvanized iron [0.152 mm], cast iron [0.259 mm], wood stove [0.183 – 0.914 mm], concrete [0.305 – 3.05 mm], riveted steel [0.914 – 9.14 mm] (after Moody (1947))
Fittings	Several – 16 count, but none inline with the straight runs of pipe	Not offered	7 count – gate valve ¼ open, gate valve ½ open, gate valve ¾ open, expansion, contraction, globe valve ½ open, globe valve fully open
Flow rate	Variable	2 count – fixed inputs	Variable (min and max to be determined)
Flow rate measurement	2 count – at discharge of pump, at inlet of pipe network	Not offered	4 count – at discharge of pump, one on each horizontal branch, at discharge of pipe network downstream of fitting locations
Flow networks	Single run of pipe (5 pipes of different elevations), parallel flow	Single run of pipe	Single run of pipe (2 pipes at different elevations), parallel flow, combined series flow

NOTE: We assume that the students can achieve a particular flow, however, some values cannot be achieved because the pump, as programmed, does not have enough power. For this reason, the maximum flow rate remains to be determined.

As Table 1 makes clear, the digital twin produced has more capabilities than the Edibon AFT-B Fluid Friction in Pipes unit and the initial digital twin developed for the pilot. It is, as a result, more flexible and versatile. The capabilities programmed make a wide variety of use patterns possible. And, since it is digital, there is no need for cleaning and maintenance, a dedicated use and storage space, or purchase of supplies and materials. Combined these represent expanded capability, increased efficiency, and lower cost.

Design and Development

Hardware and Software Considerations

Table 2 shows the hardware and software requirements for the Mixed Reality Labs. Additionally, it was important to consider deployment of the MR Labs in a classroom context. To that end there were some infrastructure improvements initiated at the University. First, we were granted an open, covered space with the capacity to contain 25 adults to facilitate their free movement while they were interacting with the digital twin in the performance of their respective labs. The HoloLens itself has no special connectivity requirements; it contains a Wi-Fi 5 (802.11ac 2x2) adaptor and connects to Wi-Fi similar to a phone or laptop. However, to network the devices to provide a multiplayer capability, together with the local laptop station, it is necessary to use certain ports that may be restricted or closed by the network administrator. The headsets and local laptop must be able to see and connect to each other via IP address in the same network and the system needs to be able to access the Serl.io website and domain for it to work. To facilitate this requirement, a separate network for the devices to reach the cloud services was provided by the institution's Center for Information Technology Excellence (CITE).

Table 2. Hardware & Software Recommendations

HoloLens 2 Headset(s) running HoloLens 2 MR Labs App	Wi-Fi Need to ensure no firewalls or closed ports. Best if dedicated institutional wi-fi access granted. Cat 5.
Win 11 PC/Laptop running MR Labs Console App 13th Gen Intel Core i7 RTX 4060 16 GB RAM 1 TB Storage (all session data stored locally)	Router (if running local only) Dual Band High Wi-Fi Range (2000 sq ft or more) AC, AX, N formats At least 2.4 gigabits/sec speed
Azure Cloud storage	PVAMU MR Lab Windows 11 app (includes installation files for HoloLens 2) Version?

Figure 2a and b show the networking configurations for local and remote sessions. Figure 2a, shows two concurrent lobbies, Lobby 1 and Lobby 2, in the same location being managed by a single computer. Each lobby has its own members using individual HoloLens 2 headsets and interacting with its own MR digital twin. While the student users will be able to see one another through their respective headsets, the participants in a given lobby can only view or interact with the digital twin in their lobby (i.e., Lobby 1 participants cannot interact with the hologram in Lobby 2 and vice versa). Figure 2b shows the remote configuration for a single lobby. In this case, two of the users are in Location A and one of the users is in Location B. To facilitate a session or Lobby for remote collaboration, both locations would require a session laptop. This makes it possible for students to be unrestricted in respect to who they work with in any sessions in the labs.

As alluded to earlier, this first iteration of the Mixed Reality Labs to be used in CHEG labs at PVAMU is initially being developed as separate from the institution's CITE system and therefore will not use institutional credentials to avoid dealing with data security issues. For user management, Serl.io created a user management database and administrative interface where roles, privileges and responsibilities are assigned to allow addition of new users and assignment or reassignment of passwords. The database and administrative interface are hosted on the Serl.io domain.

Each laptop that administers a session needs to have the Mixed Reality Labs app downloaded on it. Before a student can run the lab, the students who are enrolled in the course and listed on the database must select their name (their unique ID) and enter the corresponding

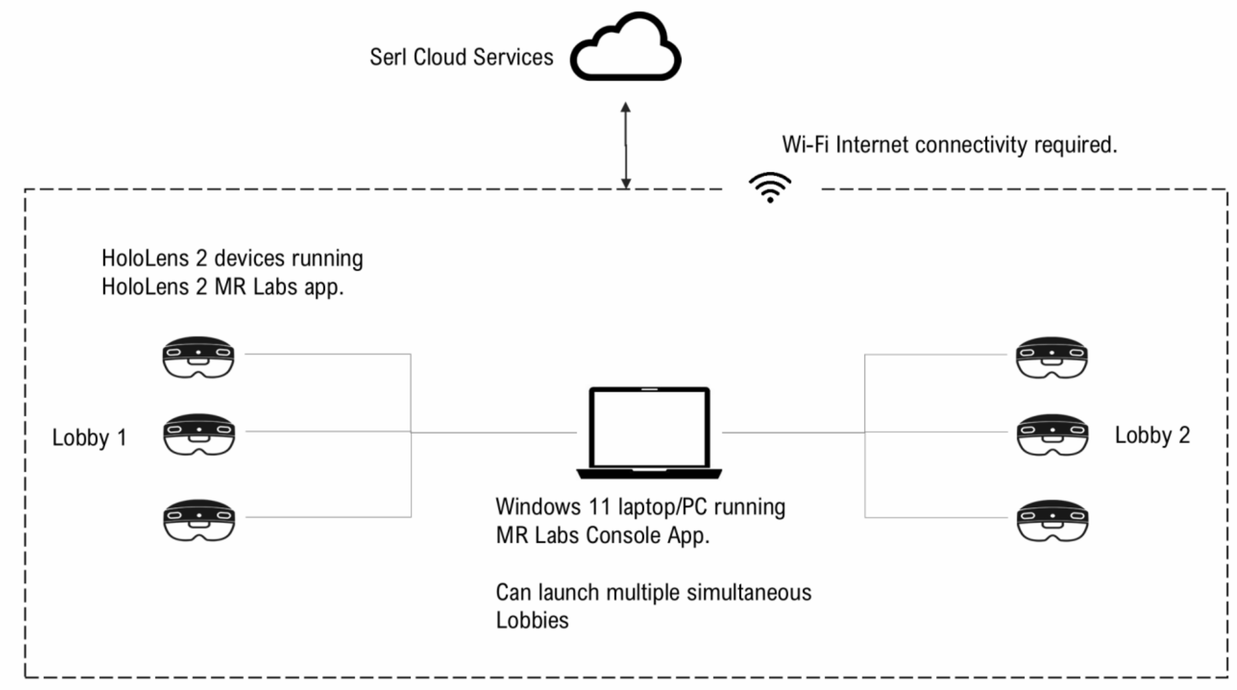

Figure 2a. Networking configuration showing local sessions.

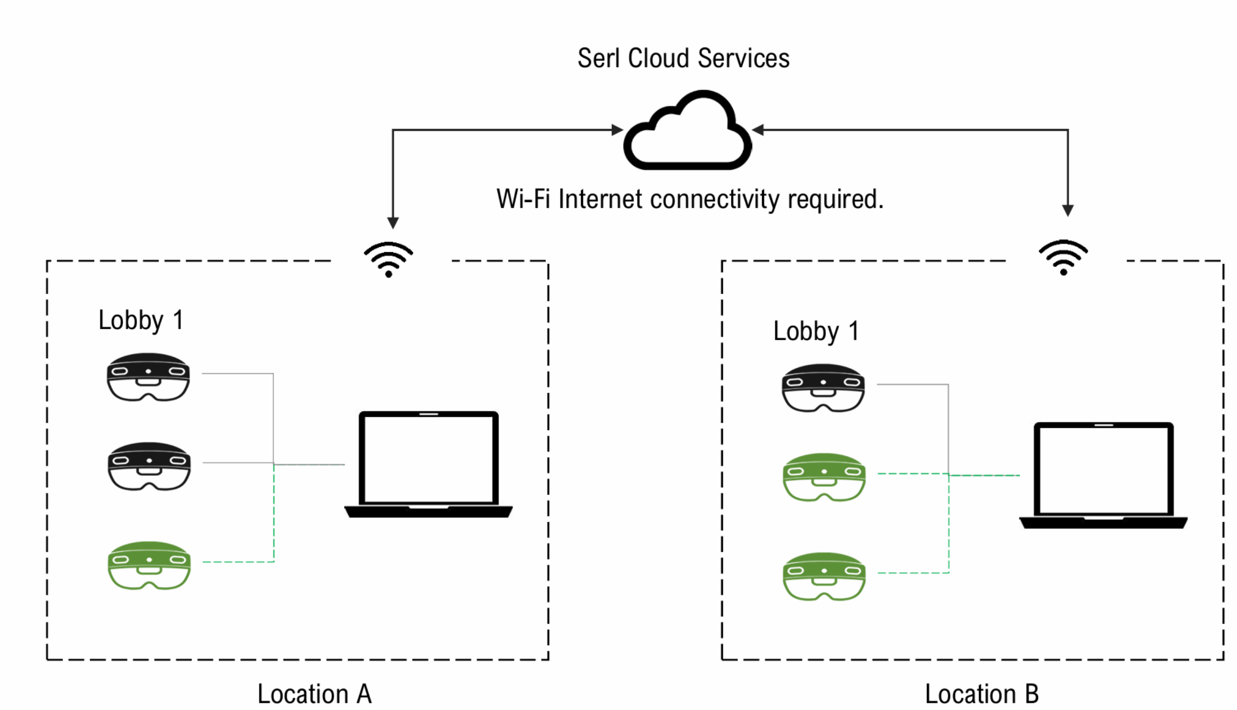

Figure 2b. Networking configuration showing a remote session or Lobby.

password specific to that ID. In this way, MR setting credentialing is used to control access to the Mixed Reality Labs app. The student's name would be used as the identifier for analytics. The Mixed Reality Labs app logs the number of instances the students accessed any of the MR Lab Modules and tracks how the students interacted with the MR digital twin during a session. It can also track local or remote use, who initiated the lobby and who are the members in a given lobby.
It is because of the requirement to track student usage of the Mixed Reality Labs app that the team determined that it was necessary to proceed with a cloud-based approach to deploy sessions (refer to Figures 2a and b).

Data Management

Regarding saving data, it is important to note the different kinds of data that can be generated throughout the project in the implementation of the Mixed Reality Labs. In this first-generation Mixed Reality Labs app, there is no dependency on the last run session or on the identity of group members who participated in a previous session. This is important as students are not restricted to who they are working with in any of the lab sessions. We avoid this dependency by eliminating the option to save intermediate or incomplete labs. If a lab is not complete, the data are not submitted to the cloud by the users, upon restarting a session, the session starts from scratch. This avoids configuration management complexities associated with managing saved scenarios where the participants intermittently save specific information about how they used the app, even though the users may have worked as a group. All data inputs are recorded to the cloud when the lab has been completed, thus maintaining each lab as discrete. The types of data generated are shown in Table 3.

Table 3. Types of data generated through use of the Mixed Reality Labs app.

Types of data	Storage Location
Lab metadata	Serl Cloud
Student interactions in lab	Serl Cloud
Student results inputs	Serl Cloud
Captured Images / video	Serl Cloud
Results of lab (scoring to be provided by University system)	Canvas
Local only or remote sessions	Serl Cloud
Total number of sessions attempted and completed for each lab	Serl Cloud
Total number of attempts and completion for each student for each lab	Serl Cloud
Total number of pass / fails / incompletes for each lab	Serl Cloud

Conception of a Digital Twin (Mixed Reality Hologram)

The use of the MR digital twin is intended to be as representative as possible to the real-life use of the physical equipment. To that end, the instructors provide a lab assignment with objectives and instructions to all students, who will later work together in groups. Typically, the students work together in groups of 3 to 5 members. Depending on the flow configuration (single run, parallel or combined series), the lab instructions will detail which valves to leave open or closed. The inputs are the fluid, pipe length, internal diameter, and pipe material (for roughness). Once the fluids mechanics flow digital twin is set up, the digital pump is turned on, and the flow rate is selected. The students in a group can then record the pressure readings at the different pressure taps (11 total) by placing the pressure gauges at the different pressure taps and sending the readings to a data sheet. Students obtain the data pressures as a function of volumetric flowrate for the various flow configurations, for given fluids, and fittings. We envisioned the digital twin to have greater flexibility than the physical equipment (Table 1).

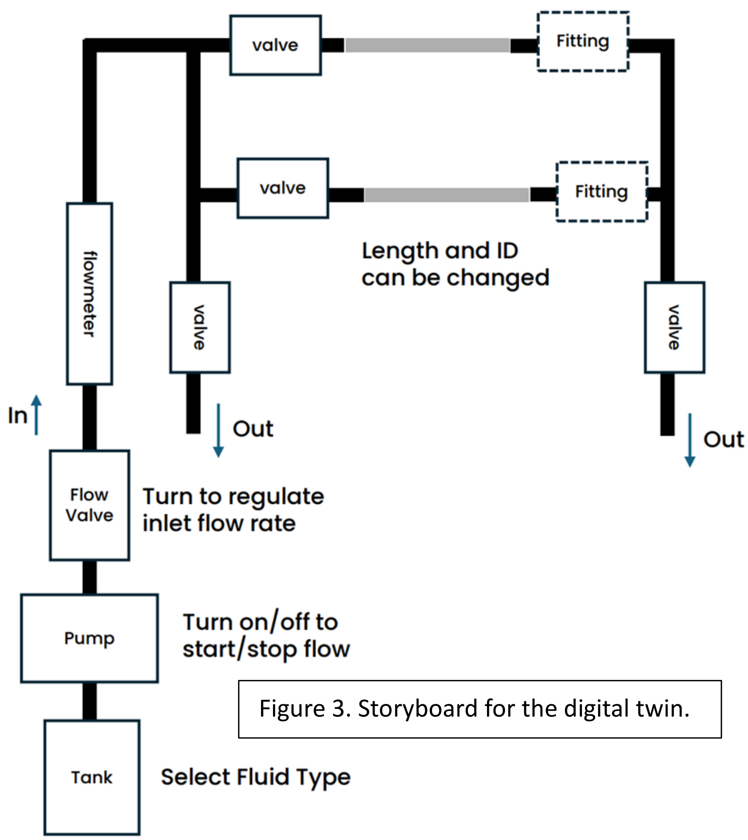

Figure 3. Storyboard for the digital twin.

The PVAMU CHEG team came up with the concept of the digital twin in its current form, providing direction on the number and location of branches, valves, pressure taps and fittings. This was followed by the storyboarding process (Figure 3) where we worked iteratively with Serl.io to develop the current iteration of the digital twin. The schematic of the digital twin and the mixed reality digital twin seen as a hologram being used by members of the project team are shown in Figures 4 and 5, respectively. At present only CHEG MR Lab 1a was piloted in

CHEG 3302 Unit Operations. The research data are discussed in another paper (Preuss et al., 2025).

Next the CHEG project team developed the logic sequence for providing the simulated results for pressure readings and flow rate readings based on empirical data of the pump characteristics of a lab-scale centrifugal pump. The logic sequence or algorithm for single flow, parallel flow and combined series flow is described in the Algorithm section below. Although not explicitly described in the algorithm section, the logic sequence includes the open/close orientation of the valves to effectuate the various flows through the piping network. Bounds on flow inputs were provided by CHEG team members based on their empirical experience in running the physical lab. These bounds govern the resultant pressures that are displayed by any given simulation.

Once the logic sequence was determined, initial coding was done in FORTRAN and followed up in MATLAB. The mixed reality digital twin was developed with Unity, a 3D game engine. To give the digital twin its functionality, the MATLAB code was provided to Serl.io and they hardcoded the logic into Python and then into Unity to give the mixed reality digital twin its functionality. A major issue was that the MATLAB script is structured to sequentially ingest user inputs to provide sequential output of the pressures and flow rates. By rescripting in Python, it was possible to ingest inputs in a batch to support "real-time" display of readings when flow starts in the Mixed Reality simulation.

The effort required to bring the MR digital twin concept to fruition is not to be underestimated. The design and development of this first version of the Mixed Reality Labs app, suitable for use in course instruction in CHEG and ECE, required roughly one year of effort with a highly technically-skilled and experienced project team of six individuals with a diversity of backgrounds; a highly skilled developer team of roughly five individuals; the voluntary participation of other individuals outside of the project team for beta testing and hundreds of hours of effort. Testing of the MR modules has been performed iteratively: 1) the developers at Serl.io; 2) undergraduate student research assistants at PVAMU paid for by the NSF grant; 3) the voluntary efforts of a graduate assistant and educators in the electrical and computer engineering department; and 4) members of the project team to check for run progression of an MR lab module. The results of the test are fed back to Serl.io for continuous refinement of the MR lab module. Currently, as beta testing is still being undertaken, the final results of the simulated individual pressures at a given pressure tap are presented without random errors. There is a plan to incorporate random errors in the pressure readings to introduce some realism to the MR experience, before handoff of the Mixed Reality Labs to the PVAMU project team. Apart from ergonomics issues discussed in the Results & Discussion section, there are no known safety issues with using the simulation.

Implementation – Lab procedures & Student Learning Objectives

Four fluids mechanics modules were developed. The labs were conceived based on the student learning objectives that we wanted to achieve:

1. Understand the influence of flow velocity on flow regime pattern – laminar, turbulent for fixed pipe geometry and fixed fluid properties.
2. Understand how friction (pressure drop) changes with velocity for a fixed pipe geometry.
3. Understand the influence of geometry of pipe (length, diameter and roughness) on pressure drop and flow regime pattern.

4. Understand the Influence of fluid properties (kinematic viscosity = viscosity/density) on flow.

Each module is a complete laboratory exercise and consists of lab instructions for students to conduct tests/experiments to measure and record data. The recorded data will be submitted as results and will determine if the lab module is completed or attempted but incomplete. Student(s) are free to do any lab modules or even redo the ones that they have completed. If a student does not complete a lab module, the lab will be submitted as incomplete and if they attempt to redo it, they redo it from the beginning (i.e., what work they had done previously in the lab module will not be saved). Each lab module can be completed in about 45 minutes. They are:

1. CHEG Lab 1a – Single Run top pipe.
2. CHEG Lab 1b – Single Run bottom pipe.
3. CHEG Lab 2 – Parallel flow.
4. CHEG Lab 3 – Combined series flow.

These CHEG MR fluid mechanics lab modules were created to be utilized in the courses, CHEG 3302 Unit Operations, a 3-credit, junior-level, prerequisite lecture course with a focus on fluid mechanics concepts for the senior lab and CHEG 4101 Chemical Engineering Laboratory II, a 1-credit laboratory course taught to seniors which included fluid mechanics practicals. Each of these modules allowed for the user to investigate the influence on the pressure drop of adding up to two fittings in series in a single pipe. The modules also allowed for the user to investigate the effect of different fluids on the pressure drop.

Along with the lab manuals provided to the students, there were skills-based tests, self-assessment surveys and self-reflection questions administered to the students as means for assessing the effectiveness of the MR digital twin. The results of these instruments are detailed for the in-class trial of Mixed Reality Lab – CHEG Lab 1 in CHEG 3302 Unit Operations in the Fall 2024 semester in another paper (Preuss et al., 2025).

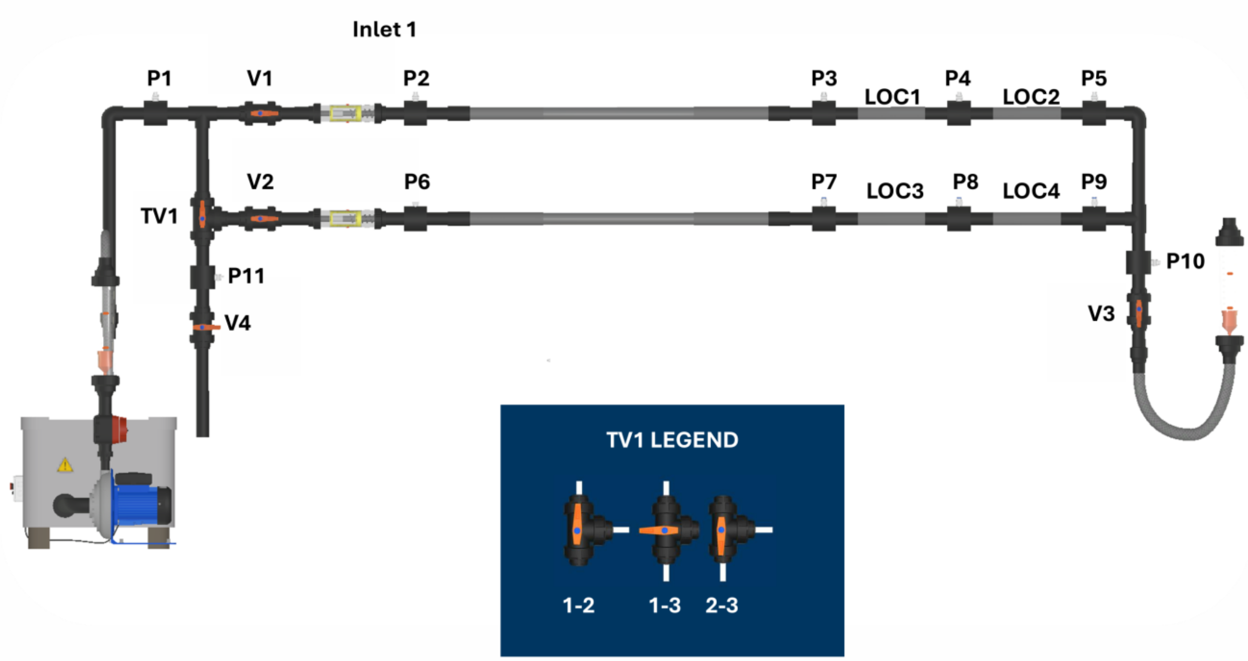

Figure 4. The schematic of the digital twin showing the centrifugal pump and reservoir along with the piping network. The pressure taps are indicated with the prefix P; the valves are indicated with the prefix V. TV1 is the 3-way valve.

Figure 5. Two members of the project team testing a working MR digital twin of the fluids mechanics equipment.

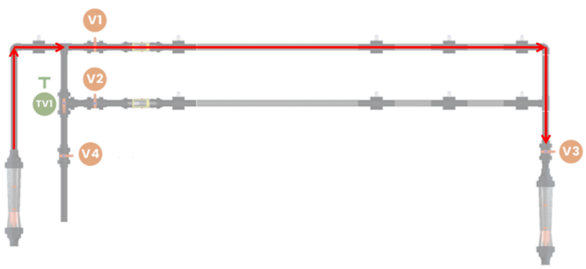

Figure 6a. CHEG MR Lab 1a – series flow single run top pipe.

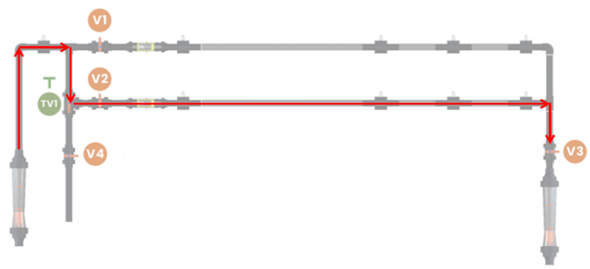

Figure 6b. CHEG MR Lab 1b – series flow single run bottom pipe.

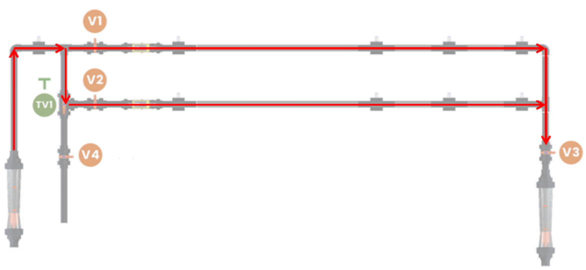

Figure 6c. CHEG MR Lab 2 – parallel flow.

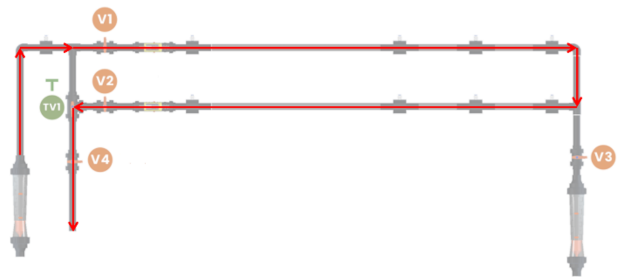

Figure 6d. CHEG MR Lab 3 – series flow top pipe.

Figure 6. The arrows show the flow of the fluid in the pipe network.

Algorithm

Step 1

<u>Calculate the pressure at point 1 (P1) from pump characteristics of a lab-scale centrifugal pump.</u>

a. Assume pump has enough power to produce an acceptable value of pressure at point 1.
b. Assume h_f in line from pump to point 1 can be calculated from the number of fittings, lengths of pipes (before the pump and after the pump). See Figure 7.
c. Calculate v_1 from flow rate and pipe diameter.
d. Apply the mechanical energy balance between points 0 and 1 on Figure 7.
e. Using Pump head vs. flow curve for the centrifugal pump (Figure 8), where pump head can be estimated for any volumetric flow rate to calculate P_1.
e. Proceed to either Step 2 (single run flow) or Step 3 (parallel flow).

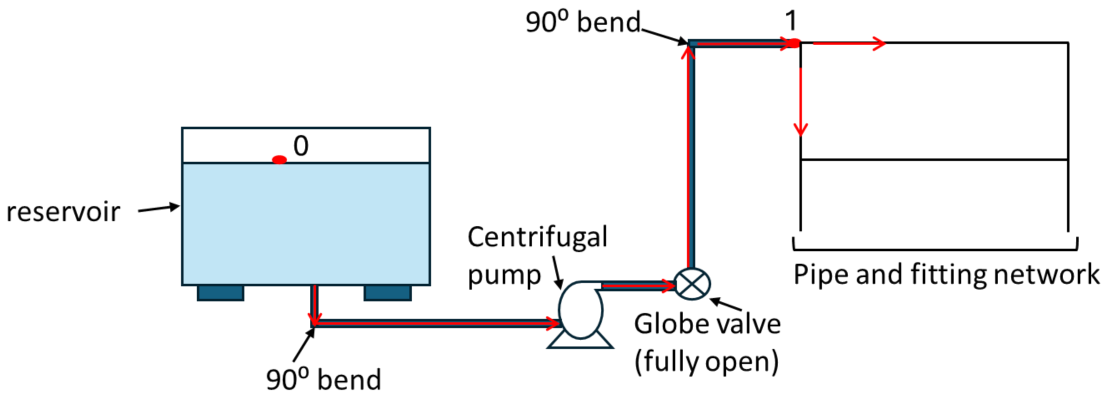

Figure 7. Schematic showing the flow of fluid from the reservoir through the centrifugal pump to the piping and fitting network of the digital twin. This schematic is not to scale.

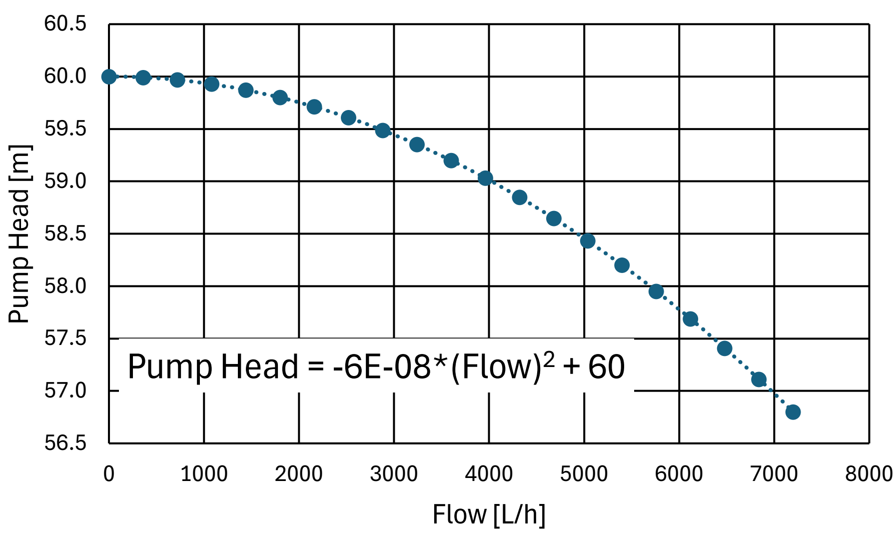

Figure 8. Pump head as a function of volumetric flow rate for a lab-scale centrifugal pump. The equation for the curve of the pump was calculated from experimental data.

Step 2

<u>Estimation of the individual pressures for a single pipe with fittings (Figure 9)</u>

a. Input a flow rate, Pipe length, diameter, roughness (depends on pipe material), fluid density, viscosity
b. Calculate the pipe velocity using continuity equation
c. From velocity then calculate Re (use fluid properties and pipe diameter)
d. Calculate relative roughness from dimensions and pipe materials (tabulated data).
e. Use Churchill equation to find friction factor, f for both laminar and turbulent flow for the straight pipe.
f. Find the minor losses, K of the fittings of interest from a reference text (e.g., Perry's Handbook Table 6-4). Note that there are 2 fittings maximum per branch on the digital twin.

g. Find friction loss, h_f in meters from f and K. Note that friction factor and minor losses are additive. We define the friction head as a combination of friction in straight pipes, given by f, fittings, given by K and inputs and outputs.
h. With knowledge of the length between points 1 and 2, use the mechanical energy balance to find the pressure drop between these two points.

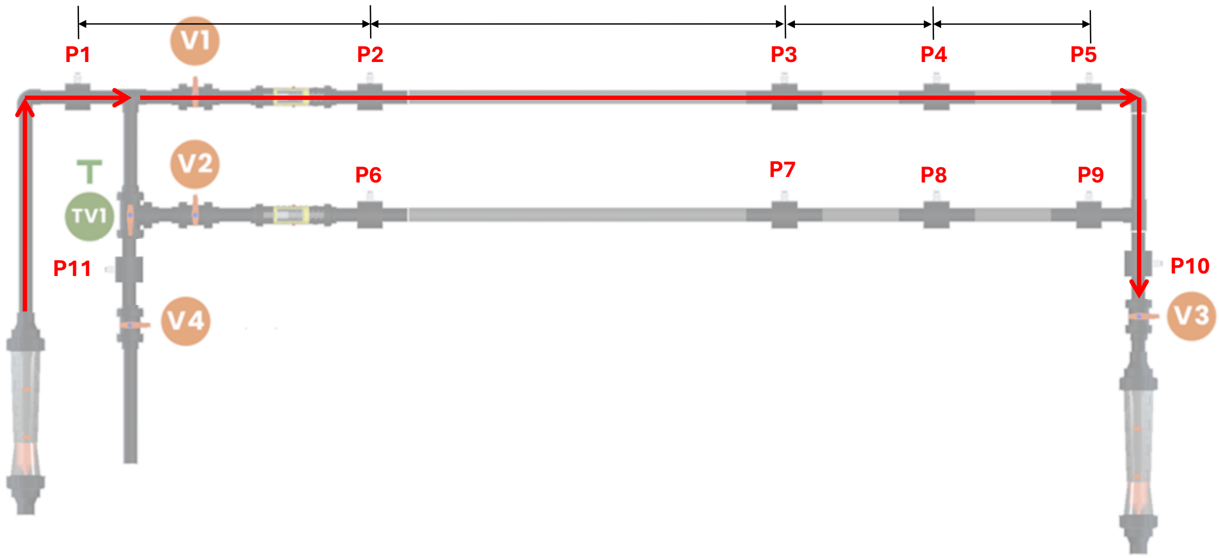

Figure 9. The flow of fluid through the top branch of the digital twin.

i. Find P2 by subtracting the pressure drop from P1.
j. Repeating steps a through i for different adjacent points (e.g., P2 and P3, P3 and P4, etc.) will yield the individual pressure values.

It is important to note that it is essential that a good estimation of $P1$ be obtained so that it is possible to calculate subsequent values of pressure using the mechanical energy balance to estimate the pressure drop.

Step 3

<u>Estimation of the individual pressures for two pipes in parallel with fittings (Figure 10)</u>

NOTE: The same fluid is flowing through both branches. The internal diameters of both branches may be different from each other.

a. Perform steps a through h of Step 2 for the top branch performing the mechanical energy balance between points P1 and P10 (see Figure 10). The fittings that must be included for the calculation of h_f are 2, T-junctions, a ball valve and a 90º bend. Include other fittings between P3 and P4 and P4 and P5, if required.
b. Perform steps a through h of Step 2 for the bottom branch performing the mechanical energy balance between points P1 and P10 (see Figure 10). The fittings that must be included for the calculation of h_f are 2, T-junctions, a three-way valve and a ball valve. Include other fittings between P7 and P8 and P8 and P9, if required.

c. Note that the pair of simultaneous equations, eq. 1 and eq. 2, must be satisfied to calculate the individual pressures.

$h_{f1,10}(top\ branch) = h_{f1,10}(bottom\ branch)$ (eq. 1)

$Total\ flow = Flow\ (top\ branch) + Flow\ (bottom\ branch)$ (eq. 2)

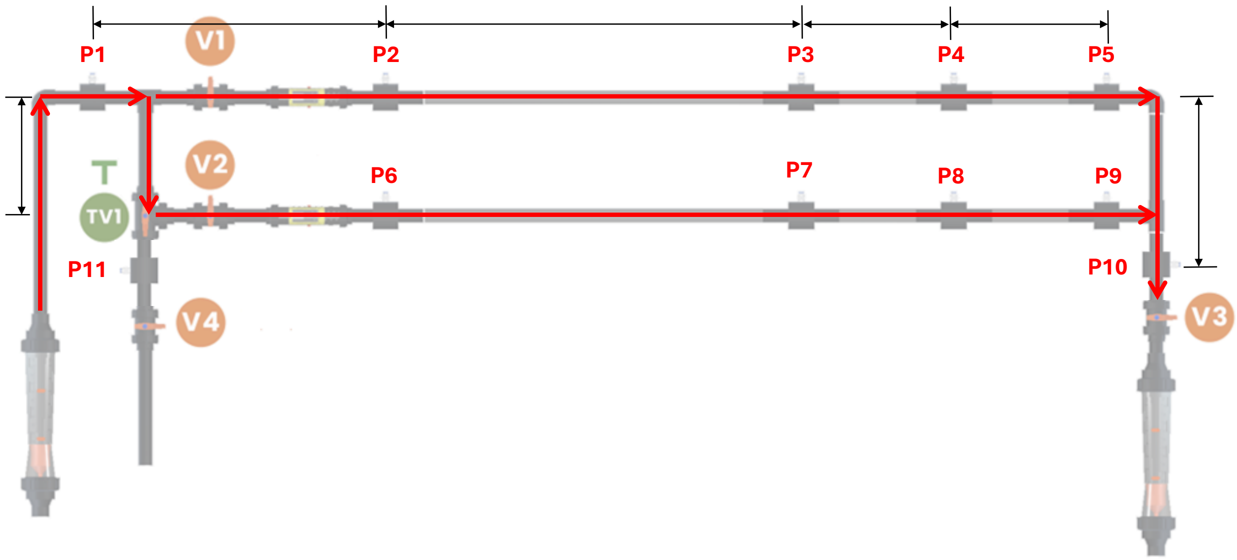

Figure 10. The flow of liquid through both branches of the digital twin. The liquid splits upstream of V1 and recombines at the T-connection upstream of P10.

Step 4

Estimation of the individual pressures for series flow through 2 pipes with fittings

a. Perform steps a through h of Step 2 and apply the mechanical energy balance between points P1 and P11 (Figure 11). The following fittings must be included in the calculation of $h_{f1,11}$: 2, T junctions, 2, ball valves, 1, 90º bend and 1, three-way valve. Include other fittings between P7 and P8 and P8 and P9, if required.

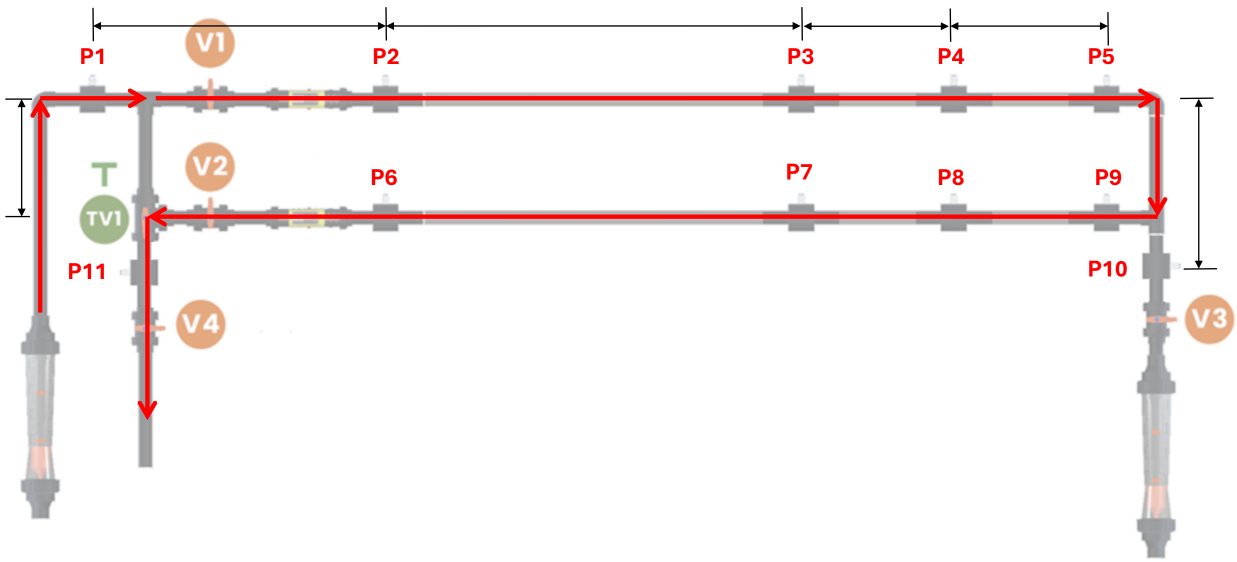

Figure 11. The flow of liquid through both branches of the digital twin in series. Use is made of the three-way valve TV1 to allow all the flow through P1 to flow through valve V1.

Results & Discussion

Herein, we will briefly describe the effect of the use of CHEG Lab 1a (Single Run top pipe) on the students in the CHEG 3302 Unit Operations course. It is important to reiterate that as an initial and limited study, conclusions drawn must be viewed as tentative and in need of verification. A comprehensive description and analysis of the implementation of CHEG Lab 1a (Single Run top pipe) is presented in our paper (Preuss et al., 2025). To summarize, there were 24 students enrolled in the course, and we had a 100% completion rate of all the assessment instruments. The general results were strongly positive. The self-assessment queries covered topics addressed throughout the course that were related to the themes described in the Implementation – Lab procedures & Student Learning Objectives section. The skills tests required the students 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 $p = 0.0001$.

The students' sense of ability increased across the general spectrum of instructional objectives. 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.

Student feedback from implementation of the mixed reality lab was quite helpful. The mixed reality labs promoted social interaction and collaboration among the students. This supports the findings of the study (Han & Bailenson, 2024) which states that many aspects of social interaction transfer into virtual reality and can be adjusted and enhanced as necessary.

Feedback from students also 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 a mixed reality lab containing course content with student learning objectives. The process of familiarizing themselves with the technology slowed them down.

Consideration of the ergonomics of using the mixed reality platform, in particular the HoloLens 2, needs further evaluation, as several students reported headaches and being uncomfortable with using the headsets. This is also a point that can be addressed during the initial onboarding or familiarization with using the headset. The HoloLens 2 has a flip-up visor that would allow the user to take breaks from the mixed reality environment during a session. Special attention will be called to this feature during onboarding, to allow the students to take intermediate breaks during a mixed reality lab session, thereby taking into account student comfort. This act will allow students to reestablish equilibrium, per their individual requirements or during synergistic activities such as discussing the theoretical aspects of the lab with one another or performing offline calculations.

We have discussed using MR modules to bring a practical aspect to theoretical lectures as a mode of implementation. This is the principal path that we will follow in this project. Future implementations in this study will involve the collection of control data from historical incidences of teaching the courses (without MR) under study – CHEG 3302 Unit Operations and CHEG 4101 Chemical Engineering Laboratory II. Further, the project team plans to perform a repetition of CHEG Lab 1a in both the Unit Operations course (with the same instructor) and the senior chemical engineering lab course for increased confidence and statistical power. Additionally, we plan to have the students complete the other lab modules, which will enable the collection and evaluation of more data and will allow us to determine the usefulness of the mixed reality labs for improving learning. Adjacent opportunities for use include administering the mixed reality labs in the mechanical and civil engineering disciplines which have core courses with similar fluid mechanics course content as part of the curriculum.

While faculty feedback is still required, anecdotally, we can say that the introduction of MR in the Unit Operations course made the faculty more fastidious in the course preparation. This may be due to the fact that the project team, which included the instructor of record, developed the student learning objectives, the pre- and post- self-assessment surveys and the pre- and post- skills tests. Thus, advanced knowledge of what the student was required to know to perform well on these assessments, provided the added impetus to tailor the course instruction. Incorporation of MR as an educational technology tool along with the use of assessments provided the environment for the faculty to utilize the constructivist approach (albeit unintentionally) in course instruction (Allen, 2022 and the references within).

It is worth noting, however, that there are other methods of implementation, three of which we will describe below. Following successful completion of the proposed curriculum development and research, each will be part of future interactions of MR application at PVAMU. They are ordered from most immediate to most distant in terms of implementation.

Using MR as a support tool for in-person labs. It is possible to enact portions of labs as MR enabled rather than using MR for the entire lab. In this case, students doing a physical lab can pause the lab to introduce MR aspects to aid understanding of abstract concepts. Maintaining an emphasis on the physical lab might be necessary when students need to develop the ability to effectively manipulate (set up, tear down, move, add components to) real-life equipment. In this way, using MR as a critical step in an existing lab instruction to enhance understanding, increase the number of users who can be involved, or increased safety can be achieved. A process like that described could be implemented in a synchronous learning mode so all students have MR "assistance" in a just-in-time manner. This application can be scaled from one course component up as desired by the instructor.

Using MR elements as stand-alone pre-labs. MR implementation can also be employed to have students do a prelab before coming into the physical lab to complete practical experience. This mode would supplement or replace current practice whereby students read through the lab instructions and answer questions related to the lab theory bringing a practical aspect to a normally theoretical exercise through MR implementation. This prelab activity could be done asynchronously and individually based on student wishes and schedule prior to the lab period. Another application for courses with inherent safety risks would be an MR enabled prelab used to emphasize the importance of safety by incorporating scenarios with inherent risk. An ECE example is the Power Lab taught in ELEG 4102. Currently, the software-based prelab is a 2D rendition of the lab and is used to teach safety techniques. The students are taught how to avoid electrical shocks, how to handle instruments, how to make connections, what unsafe conditions are, and how to maintain a safe environment. Implementing the prelab in MR would provide an immersive yet safe experience before students attempt real-life implementation.

MR labs in place of in-person labs. It is also possible to complete entire laboratory experiences in MR. This might be enacted for settings where only remote work is possible or for which the physical equipment is rare, expensive, or fragile. While extensive time in design and development would need to be invested, it is conceivable that labs will be conducted this way. It would be especially applicable for remote learners, topics in which unusual, difficult to replicate, hard to access (e.g., remote or subterranean) or rare circumstances are required or in which there is inherent danger like practicing medical techniques or working with explosive elements. It is, though, a process that may be realized in the future much like the holodeck of the US Enterprise on the Star Trek series creating immersive settings true to life in a wide variety of contexts limited only by the creativity of the developer and the need or education level of the student.

Conclusion

The intent of this paper was to convey the design and development of a mixed reality digital twin for fluid flow in pipes to be used as an instructional tool for students learning fluid mechanics. While this effort was undertaken under the purview of the Chemical Engineering department, fluid mechanics is a course that is also taught in the mechanical and civil engineering disciplines and as such, the tool's usefulness can be extended to those departments as well.

The development of this tool is a full-on design process that is quite complex, requiring extensive subject-specific expertise, diversity of experiences, wide-ranging collaborations and hundreds of hours of effort. This effort also required institutional buy-in to provide access to student subjects, access to facilities and infrastructure upgrades that will persist and benefit future students, educators and the institution. It cannot be understated how important it was to have an energized team with the commitment to move forward to bring this project to reality. This was enabled by trust among the team members to perform their respective tasks to accomplish project milestones. A side benefit of the design and development activities is the effect on the project team members, who are also instructors of the content matter. Anecdotally, the instructors reported a heightened self-awareness of being more precise and intentional in course preparation and the communication of the subject matter.

With the implementation of the Mixed Reality Labs app, and its use in the classroom, we have inched closer to including MR as a plausible tool for bringing practical, first-person, immersive experiences to engineering education. Reiterating, with the appropriate use of MR, a student can get real-time feedback in response the student's actions because more of the learner's senses is engaged in the learning process, thereby activating more forms of learning and the potential for learning (Jacobson, 2013; Lu and Liu, 2014; Santos et al., 2016).

Next steps include the use of the Mixed Reality Labs app in other disciplines (civil and mechanical) and collecting educational research data to expand the population of users and to build confidence in use of the tool as an educational asset which can lead to successful student learning outcomes. Additionally, we have tested only one lab module and will proceed with testing the others as well to understand the efficacy of the MR digital twin and to acquire lessons learned for further development. Finally, accessing remote learning scenarios – both synchronous and asynchronous – remains a project objective.

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