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Enhancing Student Engagement in Unit Operations Laboratory through Augmented Reality

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ABSTRACT

A chemical engineering student's knowledge of theory, experimental design, and real-world processes is tested and enforced in the Unit Operations laboratory courses. However, instructors are facing challenges of delivering high-quality, hands-on laboratory content with limited resources and increasingly large class sizes. Limited in-lab time is often inefficiently allocated to individualized instruction, which broadly diminishes students' opportunity for learning by restricting the quantity of data they are able to collect. In addition, teaching in-person laboratories with social distancing measures during the pandemic posed significant logistical and safety challenges and required alternative techniques to be explored and adapted. The technological strategies implemented in this work aimed to manage laboratory course content more efficiently by enhancing familiarization, operation, and safety of lab equipment during and prior to class time. This work demonstrates the evolution of several technological tools that evaluated synchronous hybrid lab offerings and asynchronous prelab training using remote controlled cameras, web-interfaces, and augmented reality. The effectiveness of the implemented technologies was assessed via post course surveys and both negative and positive students' responses were discussed.

Key words: Mixed Reality, Experiential Learning, Remote Laboratory

INTRODUCTION

The Chemical Engineering Unit Operations (UO) course is the culmination of the chemical engineering curriculum, bridging the gap from classroom theory to the real-world industrial processes (Ballesteros et al. 2021). In the laboratory course, students participate in various stages of experiential learning including conceptualization and experimentation followed by reflection, analysis, and interpretation of data (Miller et al. 1998). Students apply the theory learned from other courses to enforce the underlying principles at play (Abu-Khalaf 2001). While equations of conservation of mass and heat transfer always hold, their conceptual and quantitative adoption to real processes must first be reconciled with the physical actions of rotating a valve or reading a temperature gauge before the content is mastered (Miller et al. 1998).

Maintaining this safe and dynamic learning environment demands infrastructure, significant training, time, and resources (Carter et al. 2019). These factors challenge educators to effectively deliver resource-intensive course content, especially in the wake of the COVID-19 pandemic as instructors urgently transitioned to either a fully virtual or limited hybrid instruction to mitigate the disruption (Jimenez et al. 2002). Chemical engineering departments around the world brought forth several solutions to foster engaging UO experiences: in-person de-densification (Luks 2021), hybrid in-person and synchronous remote lab teams (Maxson 2021), recorded asynchronous videos of instructor-run experiments for remote observation (Dietrich et al. 2020), and completely virtual simulations of lab experiments (Dua, 2021; Elkhatat & Al, 2021). Notably, many of these solutions came at the sacrifice of experiential learning, an element that has proven to be most effective through in person labs (Wiesner and Lan 2004), followed by simulations (Glassey and Magalhães 2020), and finally videos (Smith, Souto-melgar, and Clausen 2021). Increased demands on faculty time compounded with limited access to lab space warranted dramatic steps to pivot crucial aspects of the course e.g. lab content, tours, prelab reports, and faculty conferences, to more accessible alternatives.

Augmented reality (AR) systems superimpose a virtual space onto the user’s three-dimensional real-world environment via a hologram projection. An array of sensors and supporting algorithms constantly map the space viewed through the transparent lens of a computerized headset. From the point of view of the user, their surroundings now contain holograms corresponding to specific AR functionalities that can be spatially anchored to real-world structures with high precision and reliability to effectively create a mixed reality experience.

As an educational tool, AR has only been recently implemented for higher education (Martín-Gutiérrez et al. 2015). The potential efficacy of AR is realized when the interface between the physical and virtual worlds are leveraged together to form an experiential immersion into a mixed learning environment not possible by either individually (Solmaz et al. 2021). Traditionally unidirectional activities, such as refinery facility tours, chemistry lab safety training, and industrial equipment troubleshooting, are evolving to incorporate user interactivity (Zhu et al. 2018). In a quasi-virtual setting, medical students implemented AR to interact with virtual three-dimensional objects ranging from single protein structures to full scale organs as they relate to the human body (Kamphuis et al., 2014; Juan et al., 2008; Layona et al., 2018; Dreimane & Daniela, 2021). AR can improve students' understanding and expand accessibility through blending the expertise of their instructors with the theory, models, and machinery of the system at hand.

In this work, AR programs via the Microsoft Hololens 2 were implemented as part of the UO course in the chemical engineering department at a private east coast university. University-wide undergraduate student demographics are as follows: White (74.8%), Asian (11.8%), Hispanic/Latino (10.1%), Black/African American (3.2%), and American Indian/Alaska Native (0.02%). While demographics are not tabulated for the Chemical Engineering department, or more specifically the CHE4401/CHE4402 courses or survey responders, the departmental demographics are consistent with the university-reported distributions. The AR technology was employed to complement the in-lab experience for both synchronous hybrid laboratory operation and asynchronous pre-laboratory training. In the synchronous hybrid format, AR enables students to engage and experience the experiment in real time. In contrast, employing AR as part of the asynchronous pre-laboratory training allows students to visualize theoretical concepts and safely explore the lab equipment beforehand. Additionally, future AR use in the curriculum is critically discussed to highlight the potential synergy between the course content and the technology.

MATERIALS AND METHODS

UO Laboratory Courses

The Unit Operations laboratory is a three-story, 6,000 square foot pilot scale facility. It houses over 18 individual unit operations, of which nine were used in the context of this study: fluid (water) flow circuit, gas flow apparatus, packed tower, fluidized bed, membrane separator, reaction scale-up, temperature control, plate heat exchanger, and pipe heat exchanger. The aforementioned experiments are part of the senior-level core undergraduate Unit Operations of Chemical Engineering I course (CHE4401), which explores traditional bench scale and pilot scale chemical engineering unit operations. It is a primer for the more intensive Unit Operations of Chemical Engineering II course (CHE4402) which looks at more integrated systems. The course operates three times per week, with student groups of four to five members. Deployment of the AR modules occurred over two years (Fall 2020 and Fall 2021). A rotation was implemented such that each group would run a single unit operation during one, four-hour lab session each week, having pre- and post-lab reports due immediately prior to and one week after completing each lab, respectively. The first, fourth, and last weeks of the seven-week course were reserved for orientation and oral presentations, resulting in a total of four labs run per course per student group.

Several innovative technologies were introduced to develop a comprehensive hybrid teaching laboratory with augmented reality components. The lab was first outfitted with 10 high-definition pan-tilt-zoom cameras (Axis Communications P3375-V 1080p), which were carefully mounted throughout the three-story lab to provide synchronous remote controls. In the second year, the cameras were integrated into a user-controlled web interface (Gather.Town), which allowed remote access to the facility both synchronously and asynchronously. In addition, Gather.Town, a virtual online platform equipped with synchronous meeting spaces and demonstration videos, was used to offer expert introductory tours of lab equipment that students could access on their own time and at their own pace, as shown in Figure 4.

The second major piece of technology used was the Microsoft HoloLens 2 (HL2) augmented reality glasses. The HL2 glasses were mounted to the base of hard hats using Velcro straps, and used in conjunction with safety glasses, as per the safety requirements of the open bay laboratory. For sanitation reasons, the glasses were washed down with isopropyl alcohol using microfiber cloths after use, then sanitized by ultraviolet radiation for 60 seconds in a Cleanbox CX1 per manufacturer instructions. The HL2 were preloaded with Microsoft Guides and Microsoft Remote Assist.

To summarize, in the first year Microsoft Remote Assist was used on the HL2 for synchronous streaming into a Teams meeting; remote access to PTZ cameras was administered through Teams. In the second year, HL2 was strictly used asynchronously with Microsoft Guides prior to the lab period; PTZ cameras were integrated into Gather.Town alongside embedded video tutorials.

Assessment of the implemented technologies was performed at the completion of the 7-week term via post-course surveys after the second year of implementation. Optional surveys were conducted using Qualtrics web interface to gauge the overall student reception of the AR technology used in the course. Complete responses were obtained for 21 out of the 89 students enrolled in the second year; the approximately 1 in 4 response rate can be attributed to the hectic nature of the transition period between academic terms and the fact that not all students who participated in CHE4401 ended up enrolling in CHE4402.

Remote Meetings and Lab Interfacing

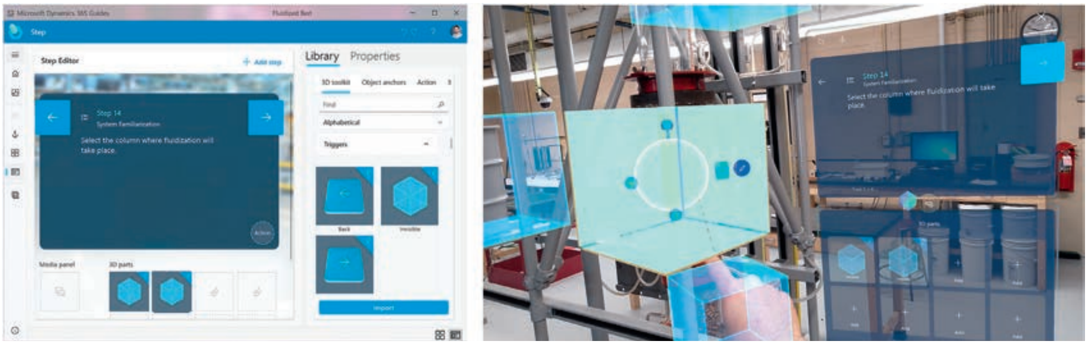
Remote Assist was used in conjunction with Microsoft Teams in the first year of deployment to facilitate real time phone calls between students in lab wearing HL2 and remote students. The student wearing the HL2 headset worked with a groupmate in lab to operate the experimental equipment and to relay process information while communicating with remote students and instructors via a Microsoft Teams call.

Remote students could view the unit operation both through the point of view of the HL2 as well as through high-resolution PTZ cameras allowing remote students to process the raw data in parallel and recommend adjustments. Real time analysis by remote students was performed in Microsoft Excel that was shared on Microsoft cloud, but also holographically streamed during meetings to the lab HL2. The user-controlled web interface Gather.Town was introduced for further visualization of the equipment. Each piece of virtual equipment was supported with asynchronous introductory video tours and synchronous meeting spaces for students to use at their own pace.

Guides Programming

Guides were constructed within the Microsoft Guides desktop software (version 603.2107.20001.0) to asynchronously teach key aspects for each of the nine unit operations. Figure 1 illustrates a side-by-side view of the programmer during the construction of the Guide and placement of the holograms in physical space tailored to their specific purpose.

The logic diagram depicted in Figure 2 was designed to ensure each Guide covers course objectives. When beginning a new Guide, a two-dimensional QR code is set to anchor the Guide in the real world. Each successive chapter tests hardware familiarization, procedure (e.g. startup, runtime, shutdown), core engineering concepts, and operational safety. Within each chapter, a series of



Step 14
System Familiarization
Select the column where fluidization will take place.

Figure 1. Programing in Microsoft Guides. (Left) desktop program writing the prompt, selecting holograms/graphics and defining actions (invisible buttons). (Right) view from programmer placing the invisible buttons in lab for the correct and incorrect selections. Buttons are shown as blue holographic boxes for programming purposes; they are invisible during student-mode.

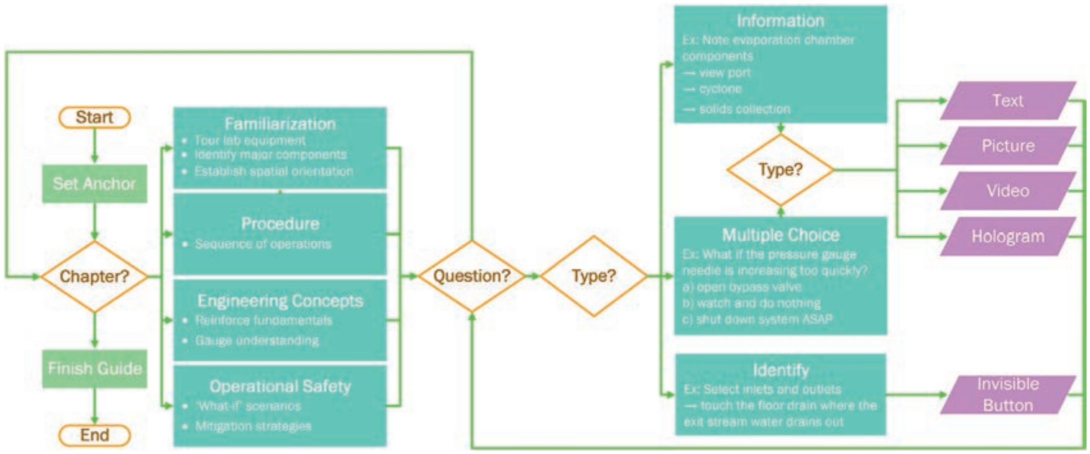


Figure 2. Logic diagram used for programing unit operations in Microsoft Guides.

prompts engages the user with either information or task-based questions in the form of holographic cards superimposed over the experimental setup.

Informational prompts are presented as text cards, pictures, videos, or holograms about the specific topic, while *Multiple Choice* questions provide the user with a bulleted list of selectable text answers. *Identify* tasks direct the user to physically reach out and touch objects in the lab, which are linked to holograms that are shown as blue boxes in author mode (programmer view) and invisible in operator mode (user view), as shown in Figure 1. Supplemental video tutorials, equipment schematics, background theory graphics, and model animations were produced separately and integrated throughout each Guide to promote visualization and facilitate critical thinking. From a user experience, Guides only reacts to user inputs, such as selecting an object, requesting a hint, or going backward. Furthermore, forward progress can only be achieved by selecting the correct answers or identifying the correct components. When implemented as a pre-laboratory activity, the AR Guide delivers the professors' expertise in a tailored training module to streamline the students' in-lab experience thereby expanding what is possible within the limited four-hour lab period.

RESULTS AND DISCUSSION

Synchronous Hybrid Lab Operation

AR in UO was first implemented to expand lab accessibility during the COVID-19 pandemic by enabling remote users to actively engage with their in-person lab partners for safe hybrid

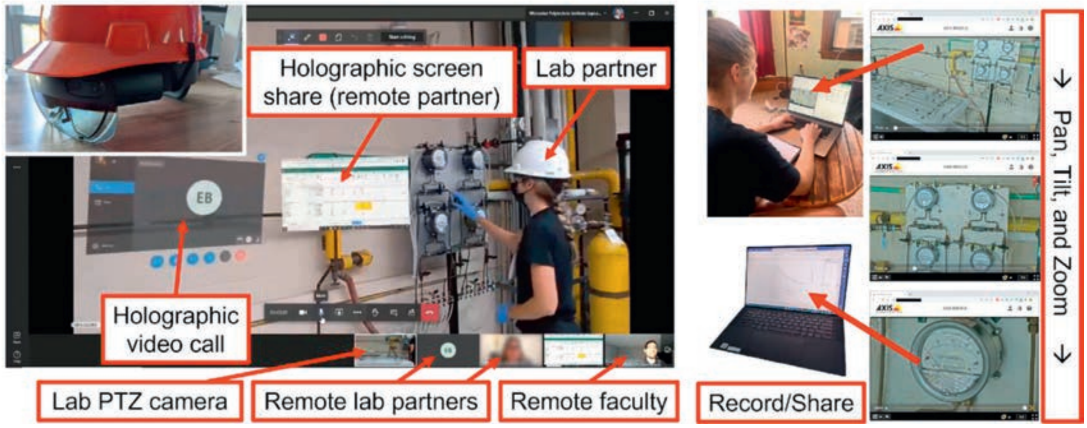


Figure 3. Left: Screenshot from remote user showing view from student wearing the HoloLens 2. Holograms of the video call and screenshare (Excel spreadsheet) are superimposed onto the lab apparatus. A second student is in lab conducting experiments, and two remote students and one faculty member are on the Teams call. Right: Lab camera is also being streamed by one user. Top Left: photograph of HoloLens 2 fixed beneath bump cap.

operation. One in-person user per group wore the HL2 to stream their real-time point of view to their remote counterparts, while their partner primarily operated the experimental equipment in lab with instructor supervision similar to the strategy executed at Hampton University (Dua 2021). Two other teammates were remote, operating cameras and participating in a Microsoft Teams meeting. The role of the remote users was to primarily perform calculations in real time and make recommendations for operating parameters. These roles within the team would be alternated weekly following the semester schedule of experiments while accommodating COVID-19 de-densification and quarantine protocols. Figure 3 shows a screen capture from a remote user receiving a live feed from HL2 wearer. In addition to video calling, synchronous data analysis performed in Microsoft Excel by remote users is shared via holographic projections in the video call. A video demonstration of AR Remote Assist during CHE4401 has been posted for public viewing on Youtube.com (Teixeira 2022a).

Synchronous AR was scaled back in the second year, while hybrid learning resources were expanded to enhance the learning of students who were unable to attend the course in person. The online Gather.Town platform shown in Figure 4 had a streamlined interface, offering students uninterrupted access to virtual private areas for remote meetings and a virtual two-dimensional floorplan of the UO lab equipped with strategically placed PTZ cameras.

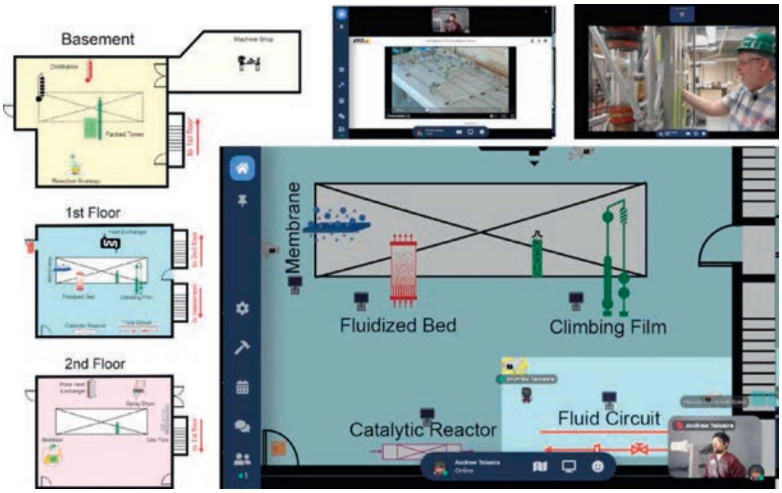


Figure 4. Students 'walk' through a map of the UO lab in Gather.Town web interface with embedded pre-recorded video tours from faculty (top right), live PTZ cameras (top middle), and synchronous group video conferencing space (main window).

Synchronous Outcomes/Discussions

Synchronous implementation of AR via Microsoft Remote Assist, Excel, and Teams was met with successes and setbacks. Overcoming the obstacles of substantial occupancy limits and forced remote work for students and professors due to COVID-19 isolation was by no means a small task. Doing so allowed remote students to actively engage in the experiment and cultivate cooperative group dynamics that are paramount to the UO course (Maxson 2021). However, technical and logistical challenges persisted in the launch of the synchronous AR. Licensing and login procedures resulted in substantial in-class delays, up to 20 or 30 minutes in some cases. Prolonged streaming also quickly depleted the HL2 battery, limiting the user to <2 hours of continuous operation. Furthermore, stationary remote-controlled PTZ cameras were preferred over a continuous first-person feed as head motion by the HL2 operator often caused chaotic, dizzying video streams. Consequently, identifying that the AR technology benefited the HL2 wearer over the remote users motivated the omission of synchronous headset streaming in favor of a more concentrated offline experience in subsequent course offerings.

Notably, however, the UO lab remained loud, so video chatting worked best with Bluetooth headsets. In both years, remote students were most engaged with data analysis and periodic discussions with students and faculty, though some groups did opt to also have them perform data collection when reasonable. More creative methods for remote engagement can explore more heavy integration with LabVIEW or similar automation platforms, though automation was intentionally minimized in most units in CHE4401 in favor of physical controls for pedagogical reasons.

Asynchronous Prelab Experience

The disruption and subsequent adjustments made in response to the COVID-19 pandemic revealed that initial in-lab familiarization was a consistent bottleneck in facilitating the resource-intensive UO course. Rather than continuing to consume valuable in-lab time with hybrid techniques, a more sustainable pedagogical approach was sought to take advantage of pre-lab time to deliver course content asynchronously while promoting deeper understanding of the UO experiments.

High precision PTZ cameras capable of resolving millimeter-scale measurements were coupled with video tours and made available to students via the Gather.Town platform shown in Figure 4. Floor maps from Gather.Town (left) as well as a larger view of the 1st floor are listed with one participant engaging with a lab camera. The camera feed is shown inlay (top middle), while embedded faculty videos are distributed throughout the map, and stream when engaged (top right). A video tutorial outlining the navigation and operation of the Gather.Town platform has been posted for public viewing on Youtube.com (Teixeira 2022b).

AR Guides were interactive tutorials designed to simultaneously teach and test familiarization of a given unit operation prior to their scheduled lab period. Guides were written to sequentially lead the user through a hands-on tour of the equipment underscoring key components involved in operation, startup and shutdown, theory, and lab safety. Text, pictures, videos, and holograms (arrows, circles, boxes, etc.) supplemented tasks where appropriate. Guide development is outlined in Figure 2, and each element of Figure 5 highlights characteristic aspects of the user experience as they relate to course objectives. Invisible buttons depicted in Figure 5A required the user to physically reach out and touch the regulator used to control the steam pressure. Pre-lab AR tours were strategically designed such that even when the Guide did not directly require physical action, the user was still interacting with course content as depicted in the instructor-led video describing startup procedures featured in Figure 5B. Conceptual questions were introduced typically as multiple choice, often aided by metadata shown holographically as a picture. Figure 5C shows an example of this where the student observes a marked-up Ergun equation and is prompted to analyze the expression. Finally, safety was introduced by asking students to identify hazards, select relevant personal protective equipment, or reflect on potential ‘what-if’ scenarios that could occur in the lab. Figure 5D demonstrates an example of a student being tested on responding to a flooding column and how to drain it before it overflows. A holographic arrow and holographic hand reveal the necessary mitigation steps needed to be performed on the physical column to the user. A walkthrough of Guide design and hologram placement has been posted to Youtube.com for public viewing (Teixeira 2021).

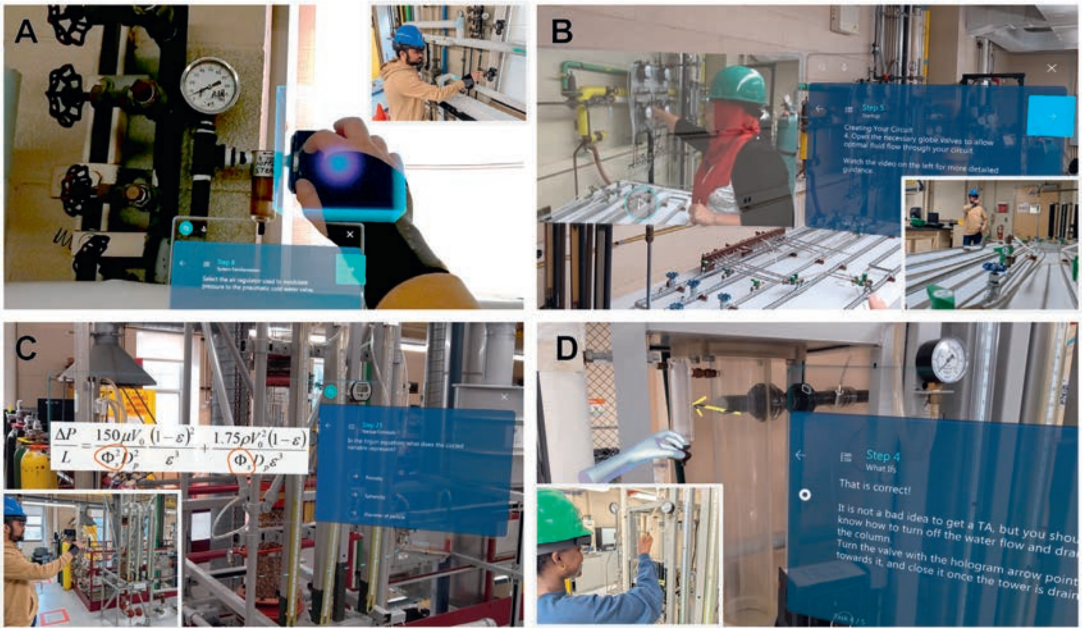


Figure 5. AR captures and photographs (insets) of the user experience for (A) Familiarization* (Identify: Invisible Button) *of shell and tube heat exchanger, (B) Procedural* (Information: Video) *of the fluid flow circuit, (C) Conceptual* (Multiple Choice: Picture) *of the fluidized bed, and (D) Safety* (Information: Hologram) *of the packed tower.

Asynchronous Outcomes/Discussions

Pre-lab Guides were explicitly implemented to improve learning by equipping users with the resources to understand the equipment, procedures, theory, and safety of any given unit operation. When executed correctly, students reported that they felt prepared before the start of the lab period and were less intimidated by the experiment setup, as supported in Table 2 where the most effective aspect of AR was "familiarization with lab equipment and components." Based on discussions with faculty, students, teaching assistants (TAs), and technicians, the following key benefits were identified for the asynchronous tools:

1. Gather.Town and AR Guides should not replace written lab instructions, physical access to the lab, or group-level meetings with instructors but rather augment these course elements to bolster the effectiveness of those course contents and sessions.
2. AR was most effective as a pre-lab tool to reduce startup time and decrease individualized faculty demand at the beginning of lab.
3. The use of short, specific pre-recorded videos in the Guides and posted online by subject-area experts are important to balance written materials.

4. AR should primarily be used to deliver familiarization, procedural, and safety information for time-efficiency and user interactivity with course content. Advanced application may be expanded to cover conceptual content secondarily.

Unfortunately, AR Guide programs were not constructed with equal rigor across the nine unit operations. While some emphasized familiarization and run-time procedures, others delved into underlying and working theory with videos and simulations. Polished Guides on complicated unit operations offered the most benefit to users especially programs whose prompts required the user to not only guess but also think about their outcome. A variety of informational, multiple choice, and identify-type questions aimed to ensure students' interaction with the system and reinforce concepts.

Student Responses

To assess the effectiveness of the new pilot technology implementations, student surveys were conducted after the second year offering of CHE4402 course. These results represent mean experiences over the semester, and it should be noted that substantial standard deviations were recorded, likely due to varying degree of program detail for each UO experiment and the technological delivery challenges discussed later.

Students evaluated their experiences with the AR technology in the UO lab in their responses to the online end-of-term survey. When reflecting on the various elements of the AR Guides, students were asked to rank the effectiveness of each, where higher scores correspond to beneficial aspects of the programs. Results shown in Table 1 highlight that participants identified the pre-recorded video introductions as their top learning aid prior to start the lab period followed by the written lab protocols, access to lab (in person), meeting with faculty/TA, AR experience, and access to lab (remote), respectively. Interestingly, standard deviation varied inversely with average ranking value. Upon closer examination, it appears that this trend aligns with how similar types of information are presented across the set of lab experiments. Concrete elements that are straightforward

Table 1. Students rank the effectiveness of each course resource in preparation for starting the lab period.

	AVG	STDEV
Pre-recorded video introductions	4.52	0.66
Written lab protocols	4.29	0.88
Access to lab (in person)	3.90	0.97
Meeting with faculty/TA	3.33	1.08
Augmented reality experience	2.95	1.25
Access to lab (remote cameras)	2.26	1.21

Table 2. Students rank the effectiveness of the AR program with respect to the five UO course objectives compared to labs without the AR component (e.g. CHE4402).

	AVG	STDEV
Familiarization with lab equipment and components	3.43	1.47
Preparing the pre-laboratory report	3.05	1.21
Reducing the time to startup/start collecting data	2.76	1.23
Reducing time with faculty/TA during lab	2.71	1.39
Understanding key concepts/theory for the UO	2.62	1.17

and inherently helpful such as instructor demonstrations are ranked higher, while those subject to variability like amounts of underlying theory between experiments are ranked lower. Tools that are extremely helpful in some instances may not be as crucial in others. Responses cover the term in its entirety, rather than a single experiment, which further accounts for the wider distributions.

A portion of students completed the two UO courses (CHE4401 Unit Operations I/CHE4402 Unit Operations II), of which the AR was only implemented in CHE4401, and their specific insight is captured in the survey responses shown in Table 2. These students were once again asked to rank their experiences with AR but this time specifically concerning how the in-lab experience compared to those labs that lacked the AR Guide training. The most beneficial outcomes for AR were observed in 1) familiarization with lab equipment and components, and 2) preparing the prelab report. To a lesser extent, students identified in decreasing effectiveness, 3) reducing time to startup, 4) reducing time with faculty/TA during lab, and 5) understanding key concepts/theory for the UO. It is worth noting that experiences varied substantially, and, in many instances, there was a bimodal distribution, indicating that students either found the tool very useful or not useful at all.

Overall, students' experience with the AR was generally positive as outlined in Table 3. Survey participants were asked to rate the holistic aspects of the AR Guides on a 1-5 Likert-style scale

Table 3. Students rate their experience for the operation of the AR program (excluding the sign-in portion) on a 1-5 Likert-style scale (1 = strongly disagree to 5 = strongly agree).

	AVG	STDEV
Fun to use	3.71	1.03
Clarity of graphics/videos/audio	3.52	1.14
Active engagement with the program	3.48	1.18
Time for familiarization	2.90	1.27
Ease of use	2.52	0.91

(1 = strongly disagree to 5 = strongly agree). The top response was that it was fun to use. After that, high ratings were given for clarity of graphics/videos/audio and active engagement with the program. Low ratings were given for the time for familiarization and ease of use, which can be attributed to the glitches that will be discussed further.

In written survey responses, two recurring rationales become evident. First, students identified other platforms (e.g. online quizzes or reports) to be better for evaluating conceptual questions. Secondly, the overwhelming number of responses identified a substantial amount of glitches either during initial program startup or operation. In the optional written responses, 3 of 7 identified major glitching problems, but in their same response they also wrote, the technology was a “really useful tool;” “AR is great and helps me familiarize myself with the physical set up prior to lab;” and “it is a great idea that, when working, is extremely helpful in understanding the lab.” The specific glitches in order of prevalence were: a) slow sign-in processes (5–20 minutes) were initially experienced due to licensing difficulties, b) poor internet connectivity due to campus network security, c) misaligned anchors/holographic objects when using different HL devices, d) blurry graphics due to poor re-calibration when switching users. Anecdotally, the cameras were primarily used after the lab period (e.g. if they missed something in a schematic) or during the lab period (e.g. if one student was remote).

CONCLUSIONS

Although AR was initially incorporated into the UO lab in response to the COVID-19 pandemic, successive iterations on the technology and techniques generated pedagogical insight as more deliberate systematic course design was considered. AR maximized in-lab time for large, resource-intensive laboratory courses by minimizing startup and faculty time. Guides served as a technical aid for preparing pre-lab reports and offered independent equipment familiarization and procedural overview prior to lab periods. AR proved less effective at delivering conceptual content than conventional instruction, as mixed reality added unnecessary features to already complicated material. Synchronous remote access was also identified to perform best when the remote users were in control, namely through a web interface with integrated PTZ camera controls; the use of live streaming devices (HL2) proved challenging for the lab student and chaotic for the remote student for prolonged periods of time.

Deliberate mixed reality course design will be needed to leverage the potential for student engagement, procedural training, and conceptual content delivery. The successful use and integration of holograms, picture/video content, and interactive mixed reality actions were demonstrated in this work; future work must take it beyond this scope to challenge the students to think critically in mixed reality space by incorporating simulations, visualization beyond the macroscopic hardware, and assessment during the program. Ultimately, the potential for mixed reality in the laboratory environment is just beginning to be realized.

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Professor Andrew Teixeira is a classically trained chemical engineer with specialties in the fields of chemical reaction engineering and materials science. He received his B.S. from Worcester Polytechnic Institute in 2009, and continued to pursue his Ph.D. with Professor Dauenhauer at the University of Massachusetts Amherst in 2014, before completing his postdoctoral studies with Professor Jensen at the Massachusetts Institute of Technology in 2016, ultimately joining the faculty at WPI in 2017. His primary research focus combines a multidisciplinary approach with classical and new experimental techniques to uncover fundamental understandings in the fields of catalysis and reaction engineering for energy and pharmaceutical sciences. Utilizing microfluidics and micro-catalytic reactors, his research group aims to unlock extreme heterogeneous catalytic performance as well as study the intricacies of dynamic crystallization processes.