Engineering Educators Bringing the World Together
2025 ASEE Annual Conference & Exposition
Palais des congrès de Montréal, Montréal, QC • June 22–25, 2025
Paper ID #48689

Development of AI-Assisted, Immersive Virtual Reality Learning Module to Enhance Operation and Procedural Accuracy for Laboratory Education

Xiaoye Michael Wang
Jackie Anjie Liu, University of British Columbia, Vancouver
TImothy Welsh, University of Toronto
Prof. Ariel Chan, University of Toronto

Professor Ariel Chan joined the Department of Chemical Engineering and Applied Chemistry at the University of Toronto in 2017. She is also a practicing professional engineer registered in Ontario, Canada. Her research focuses on experiential learning and laboratory curriculum design. She has also devoted her research to cultivating more equitable and inclusive learning using a data analytic approach to identify factors associated with engineering students' academic performance. Her teaching and research have been awarded Engineering Dean's Emerging Innovation in Teaching Professorship. She is also the recipient of the Canadian Wighton Fellowship in 2022 and the Northrop Frye Award in 2023.

Work-in-Progress: Development of AI-Assisted, Immersive Virtual Reality Learning Module to Enhance Operation and Procedural Accuracy for Laboratory Education

Xiaoye Michael Wang[a], Jackie Liu[b], Timothy N. Welsh[a], Ariel W Chan[b,*]

[a]Faculty of Kinesiology & Physical Education, University of Toronto
[b]Department of Chemical Engineering and Applied Chemistry, Faculty of Applied Science and Engineering
*corresponding author: ariel.chan@utoronto.ca

Abstract

The Unit Operations Laboratory (UOL) provides chemical engineering students with hands-on experience by applying engineering and science concepts to industry-scale equipment. The traditional physical lab environment has several limitations that hinder its effectiveness as a comprehensive teaching tool, including limited access and safety concerns. The current study proposes a virtual UOL (v-UOL) framework that enables educators to create an immersive, interactive learning environment that mirrors the physical lab, designed to supplement in-person lab courses. Using virtual reality (VR) headsets and controllers, students can navigate the simulated lab space and interact with equipment that replicates real-life scenarios. This virtual experience allows repeated practice without the safety risks or resource constraints of a physical lab, enabling students to build competence through hands-on practice. This end-to-end framework includes the creation of virtual assets replicating full-scale equipment and incorporates enhanced learning tools, such as large language model (LLM)-enabled guidance, procedural tracking, multi-user support, and performance tracking. As a work in progress, this pilot study presents a digital twin of the packed distillation column and investigates user experience in operating the equipment either on a 2D screen or in VR. Preliminary data revealed v-UOL's effectiveness in helping students contextualize the Instrumentation Diagrams (P&ID) and establish spatial awareness related to the Standard Operating Procedures (SOP), all while making the process more engaging and enjoyable. Finally, the limitations of the current setup and future directions are discussed.

Keywords: Digital Twin, Virtual-Reality, Personalized Learning, Perception, Laboratory Education

Introduction

Engineering education necessitates the integration of theoretical knowledge with hands-on practices. In chemical engineering, Unit Operations Laboratories (UOL) offer students opportunities to gain experience operating industrial equipment while applying fundamental chemical engineering principles and concepts to investigate problems associated with the equipment's components (e.g., pipe, pump, and valve systems) and various processes (e.g., heat and refrigeration management)[1], [2]. However, operating a UOL could be resource intensive. To mirror industrial processes, equipment in a UOL is large in scale and complex in design, limiting the number of pieces of equipment that a UOL can house. As a result, students need to work in large groups to rotate through equipment and experiments, potentially resulting in a misalignment between hands-on practice and the theoretical content covered in lectures. This lack of synchronization negatively affects students' ability to fully grasp the material and hinders opportunities for repeated practice, which is crucial for developing competency [3], [4], [5]. Furthermore, safety concerns also present a significant challenge in the UOL [6]. Handling real chemicals and operating complex machinery involve inherent risks and, even with supervision, the potential for accidents remains. These factors, combined with resource constraints, restrict the level of students' exposure to essential lab operations, limiting student's confidence and competence when transitioning to real-world applications.

In response to these issues, there has been a persistent and progressive endeavor to integrate virtual reality (VR) and digital twin technologies into chemical engineering education. Although VR can perturb the human sensorimotor system [7], [8] and lead to inaccurate or imprecise movements that may degrade real-world performance [9], its immersive quality offers a distinct advantage for procedural training by situating learners within the task environment and enhancing spatial awareness and task comprehension [10], [11]. Building on these strengths, previous works have developed VR applications for teaching catalytic reaction [12], chemical vapor deposition (CVD) reactor [13], and crude distillation plant [14], [15]. These applications present detailed 3D representations of chemical processing plants for students to explore and interact. Despite these efforts, VR-based solutions remain underutilized in mainstream chemical engineering education, where their application has largely been limited to visualizing 3D models [16]. This highlights a persistent need for further innovation in integrating natural interactions and realistic simulations that accurately replicate physical procedures.

In response to this research gap, while maintaining the accuracy and integrity of UOL training, our group has developed a virtual reality (VR)-based UOL training system [17]. The current study builds on this system and proposes a scalable, semi-automated virtual UOL (v-UOL) framework as a supplement to the in-person lab course. This framework allows users and educators to faithfully recreate virtual versions of the UOL and implement its corresponding Standard Operating Procedures (SOPs) for procedural training in a digital format, including on a computer screen and via a VR headset. This framework also enables the integration of large language models (LLMs) to provide students with real-time, contextualized feedback. This study will first discuss the design considerations of the v-UOL framework, followed by a description of the framework and its basic functionalities. As a work-in-progress, pilot results on the user experience from graduate-level chemical engineering students operating a packed distillation column are reported. Finally, a planned usability test with undergraduate-level students enrolled in the UOL course is described.

Design Considerations

Digital Twins: A core feature of the v-UOL framework is the faithful recreation of digital twins of industrial-scale equipment based on three-dimensional (3D) drawings. Digital twins are highly detailed, interactive, 3D representations of physical equipment designed to replicate real-world functionality within the virtual environment [18]. These digital twins include interactable components that mimic the operational behavior of their real-world counterparts, providing students with opportunities to practice procedural tasks without the safety risks or operational constraints of physical labs. Ensuring the accuracy and faithfulness of the digital twins is critical to prevent misconceptions arising from discrepancies between the virtual and physical equipment. This can be achieved by integrating the physical layout provided by the 3D CAD models with the process logic from the 2D Piping and Instrumentation Diagrams (P&IDs; e.g., [19]).

Standard Operating Procedures (SOPs): Another critical feature of the v-UOL framework is the integration of text-based SOPs into the interactable components of the digital twins to establish accurate and reliable operation procedures. By directly linking instructions to specific parts of the system, such as providing text-based reminders of relevant safety risks associated with a specific component, the framework ensures students can align theoretical steps with practical actions, enhancing procedural accuracy and operational reliability. To complement this, the framework tracks performance metrics like task completion time and procedural accuracy, while leveraging large language models (LLMs) to provide real-time feedback and corrective guidance. This tracking also enables the gamification of the learning process, turning tasks into engaging challenges that encourage students to improve their performance. Game-like elements such as progress tracking, scoring systems, and achievement badges can be incorporated to motivate learners and foster a sense of accomplishment. This combination of accurate procedural mapping and iterative feedback ensures that students master complex tasks while minimizing errors.

Collaborations: To mimic the collaborative nature of real-world engineering tasks, the v-UOL framework supports VR-based multi-user interactions. This feature allows multiple students to interact simultaneously within a shared virtual environment, enabling group-based tasks such as troubleshooting a malfunctioning system or performing complex operations that require team coordination. Each participant can take on specific roles, such as adjusting equipment settings, a process that fosters teamwork and communication skills. Real-time voice communication and shared visual perspectives further enhance collaboration, providing an experience that closely resembles working in a physical lab with peers. These multi-user capabilities also allow for instructor-led sessions, in which educators can guide students through tasks, provide immediate feedback, and demonstrate complex procedures in a virtual group setting.

The Virtual Unit Operations Laboratory (v-UOL) Framework

The proposed v-UOL framework is designed to facilitate scalable and efficient training in chemical engineering. By leveraging advanced digital tools, such as 3D CAD models, 2D P&ID, and LLMs, the framework creates an immersive virtual training environment. The framework follows a modular design, allowing seamless integration of various components, real-time guidance, and collaborative training. Figure 1 shows a diagram that describes this framework.

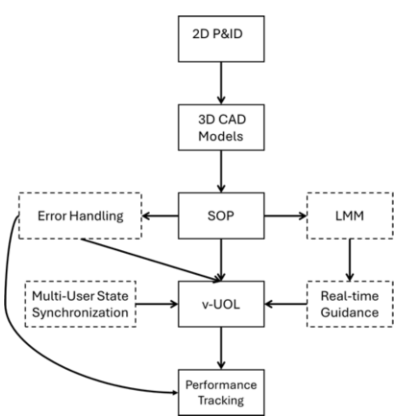

Figure 1. A diagram for the virtual Unit Operations Laboratory (v-UOL) framework. Components in dashed boxes are in-progress.

Digitization and Virtualization: The foundation of the v-UOL framework lies in the creation of 3D CAD models of physical systems and its integration with the systems' 2D P&IDs to generate accurate digital twins of industrial equipment. Creating 3D models based on 2D engineering drawings has been previously examined (e.g., [20], [21]) and various commercially available software supports this feature (e.g., AutoCAD and SOLIDWORKS; Figure 2a). Subsequently, linking the 3D models to the systems' P&ID is necessary to ensure accurate pipe routing information and the assignment of consistent component indices based on a unified indexing system (Figure 2b). This integration has been explored in prior studies (e.g., [19]) where commercial tools are available to streamline this process. Each component, such as valves, sensors, and pipelines, is assigned a unique identifier, which links its virtual counterpart to its physical and schematic equivalents (Figure 2c). The digitization enables users to interact with the virtual systems and their respective components (e.g., valves and switches) on various platforms (e.g., a computer monitor or a VR headset) with different input devices (e.g., a mouse, a controller, or the user's own hands; Figure 2d). Accurate recreation of the interaction, such as the ability to gradually turn a valve to an exact location to control the flow rate, is critical to safety training, which will be further discussed during the SOP integration stage.

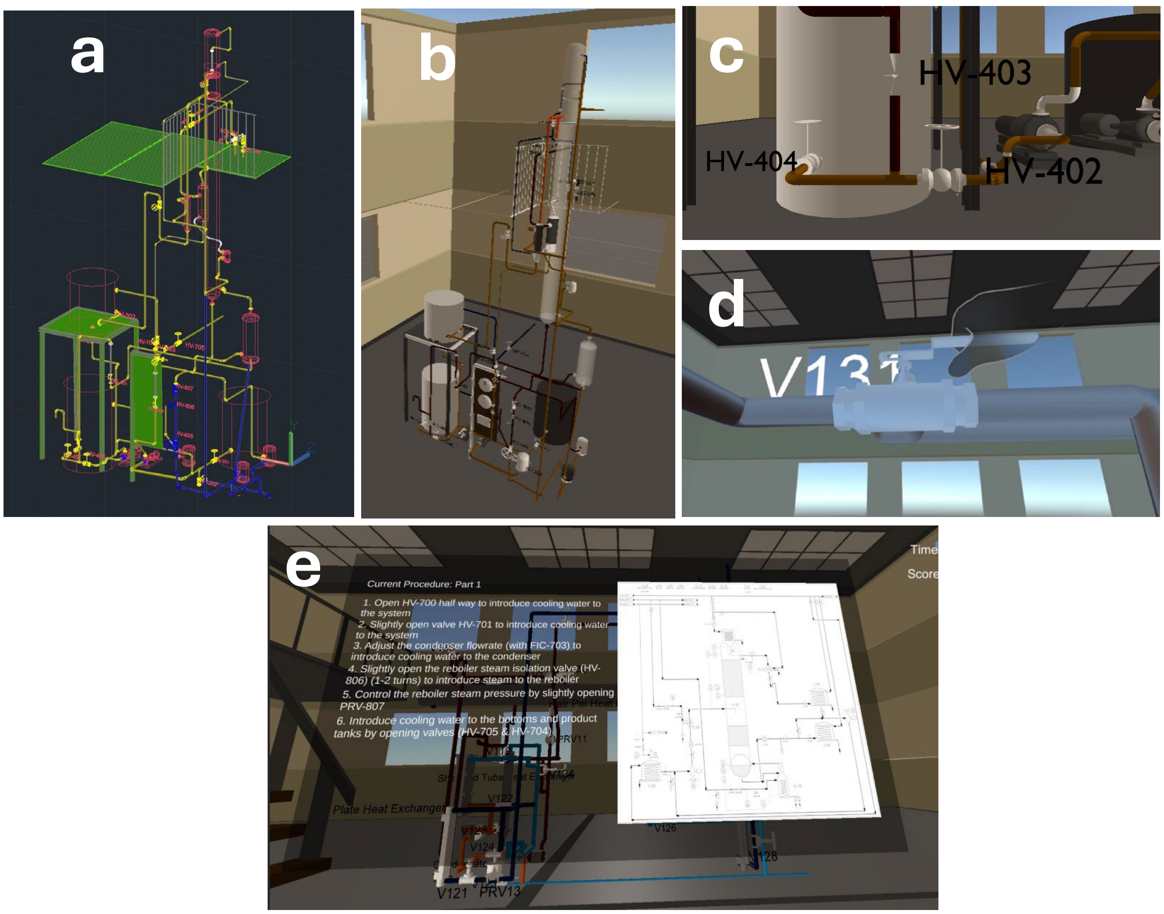

Figure 2. Illustrations of components of the v-UOL framework. (a) A 3D drawing of the packed distillation column in AutoCAD. (b) A rendered 3D model of the packed distillation column in Unity for subsequent user interactions. (c) Hand valves with labels consistent with the SOP and P&ID. (d) Direct interactions with a valve using a hand. (e) Step-by-step instructions and reference P&ID for procedural operations.

Automated SOP Integration: SOPs are essential documents that define the steps required for operating equipment safely and efficiently and are key in helping students connect fundamental chemical engineering concepts and principles with hands-on operational procedures. In the v-UOL framework, existing text-based SOPs are automatically transcribed and linked to the instrument index of the digital twin. This linkage is achieved by leveraging natural language processing (NLP) techniques and LLM to parse SOP text and map each action to the corresponding component in a 3D model based on the system's P&ID. This enables real-time comparison between the state of interactable 3D components and the SOP, helping to verify correct execution of procedures during operation. Subsequently, the v-UOL framework also uses the transcribed SOPs to dynamically generate procedural instructions in the virtual environment to provide users step-by-step instructions through the operations (Figure 2e). With the support of LLM, a voice-enabled, spatially aware AI agent can be included to provide real-time, context-sensitive guidance to users, enhancing the interactivity and accessibility of the training environment. Each step performed by the user is logged and compared with actions outlined in the SOP, enabling real-time error detection. Metrics such as task completion time, procedural accuracy, and error rates are recorded, offering educators insights into student performance. Overall, these components bridge the gap between theoretical knowledge and hands-on practice by contextualizing each step within the virtual system.

Synchronized, Interactable, Remote Collaborations: Collaboration is an essential aspect of chemical engineering education, and the v-UOL framework enables synchronized, remote multi-user interactions within the virtual environment. This feature allows users to collaboratively operate equipment, troubleshoot issues, and complete training tasks in real-time. State synchronization ensures that all users receive consistent updates to the system, regardless of their location. To facilitate effective collaboration, the framework incorporates tools for role assignment, communication, and annotation, enabling users to divide tasks and share insights seamlessly.

Pilot Study – Packed Distillation Column

In the current study, the main components of the v-UOL framework (Figure 1, solid boxes) are implemented for a packed distillation column (Figure 2b). Five graduate chemical engineering students volunteered in this study. All students have taken the UOL lab course, with two of whom being the teaching assistants for the lab course in the past 2 years. The study included two sessions on two separate days at least 24 hours apart, in which participants were asked to complete the SOP for the distillation column on a screen and through a VR headset (Meta Quest 3S) with the session order counterbalanced between participants. At the beginning of each session, participants were asked to review a paper-based SOP for the distillation column and its 2D P&ID for 10 to 15 minutes. Then, they completed the procedures in a virtual environment either on a screen or in a VR headset. After completing all steps, participants were asked to complete a post-task questionnaire to evaluate their experience, following which the experimenter conducted a brief interview to gain additional insights.

Figure 3 shows the average response to the post-task questionnaires for the VR and screen conditions. Participants rated the VR condition as more engaging, immersive, realistic, and helpful, while also finding it more intuitive to interact with compared to the screen condition. However, there were no substantial differences between the two conditions in terms of ease of interaction, comfort, confidence, stress management, or overall satisfaction. The subsequent interviews revealed several consistent themes regarding participants' experiences with the VR and screen-based conditions. Across both conditions, participants emphasized the system's value in helping them to develop the spatial awareness of the system, enabling them to locate components such as valves and pipelines within the system more easily than compared to just using the 2D P&ID. This was particularly evident in the VR condition, which was described as offering an immersive and engaging environment that facilitated an understanding of the equipment layout. The gamified nature of both conditions was viewed positively, as it increased engagement and made the experience enjoyable. Score tracking based on the successful completion of procedural steps provided a clear sense of progress and accomplishment. However, some participants expressed concerns that the gamification, especially in the screen condition, reduced focus on learning the procedural and theoretical aspects of the task.

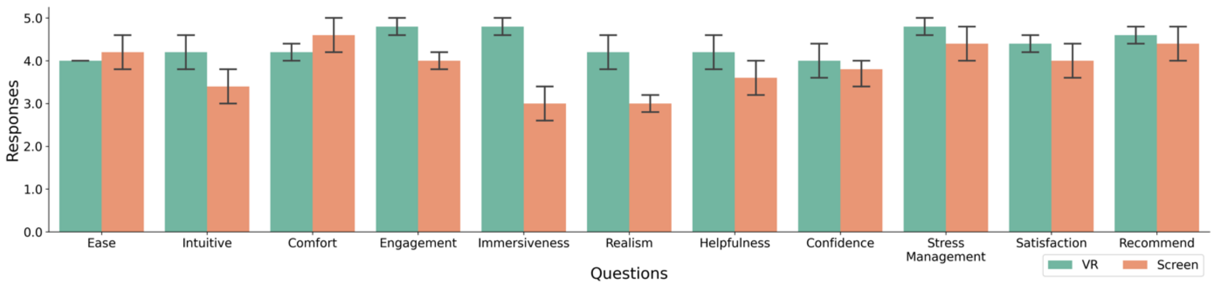

Figure 3. The average response to the post-task questionnaire. Error bars represent standard errors of the mean.

Limitations

The current study highlights the potential of the v-UOL system as a training tool for chemical engineering education, enabling students to familiarize themselves with the SOP and P&ID before engaging in physical lab activities. As this study is still ongoing, there is room to enhance the design of the user study to more rigorously evaluate its effectiveness. For instance, incorporating A/B testing could provide robust evidence of v-UOL's impact on students' preparation for lab courses. After the preliminary pilot study, the system is considered user-friendly and safe and with the ethic approval by the university committee, we are extending the study to large student body, involving over 150 third-year chemical engineering students enrolled in the UOL course, who will voluntarily participate in different pre-lab exercises. These exercises will include traditional paper-based SOP and P&ID training, as well as screen- and VR-based v-UOL applications. The study will then evaluate the student's performance, learning effectiveness, memory retention and experience during the actual lab of different v-UOL settings.

Conclusions

The v-UOL framework demonstrates significant potential as a transformative training tool for chemical engineering education. By integrating digital twins, automated SOPs, and real-time feedback using LLMs, the system bridges the gap between theoretical concepts and hands-on practice while addressing resource constraints and safety concerns associated with traditional UOL settings. Pilot results suggest that VR-based training offers a more engaging, immersive, and realistic experience compared to screen-based alternatives, facilitating spatial awareness and system understanding. However, challenges such as balancing gamification with procedural learning and optimizing user study design remain to be addressed. Future studies will further evaluate the effectiveness of the v-UOL framework across different modalities. Overall, the v-UOL framework presents a scalable and innovative solution for enhancing student preparation, confidence, and competency in lab-based education.

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