AR/VR EXPERIENCES TO SUPPORT AND ENHANCE PILOT PLANT ACTIVITIES

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ABSTRACT

Monash University Faculty of Engineering, in collaboration with the Monash Pilot Processes Student Team, are creating AR and VR experiences to complement our Membrane Pilot Plant for use in undergraduate education and industry training. We aim combine physical and digital experiences to foster a more autonomous learning environment, preparing students to handle open-ended problems effectively and with greater confidence. The digital experiences are designed to encourage students to apply the CDIO framework, particularly emphasising 'Conceive' and 'Design' stages through virtual problem-solving, before moving on to 'Implement' their new knowledge on the physical pilot plant. The concept can also be applied in reverse, where students undertake physical activities first, followed by implementation of their knowledge in the virtual environment. This paper describes our progress to date in developing and implementing the AR and VR experiences. We present the CDIO approach and standards that have informed our activity development, specifically addressing Standards 5, 7 and 8 to enhance design-implement and integrated experiences, and experiential learning. We discuss two of our digital pilot plant activities in detail: 1) a simple AR activity designed for use on a phone or tablet that is used by all engineering students in their common first year design unit, and by second-year chemical and environmental engineering students in a heat and mass transfer unit, and 2) progress on the development of a more complex VR activity that involves programming a digital twin of the process and will be implemented in a mixed reality headset (HoloLens) to train independent users of the pilot plant. We also present our proposed strategy for assessing the effectiveness of and next steps for this intervention to develop blended lab activities with complementary physical and digital components to provide students with exposure to digital technologies and improve their experience and achievement of learning outcomes associated with the pilot plant lab activities.

KEYWORDS

Augmented Reality, Virtual Reality, Laboratory, Pilot Plant, Standards 5, 7, 8.

INTRODUCTION

Augmented Reality (AR) and Virtual Reality (VR) technologies have enormous potential to enhance and support lab activities, particularly those involving pilot scale apparatus which have limited user scalability and accessibility. The use of AR involves overlaying digital information onto the real-world context, often with live data populating the experience, whereas VR immerses users in entirely virtual environments where data is typically simulated. Both technologies contribute to experiential learning, enabling students to engage with content in dynamic and meaningful ways. AR, VR, and related digital technologies are also increasingly common in industry and society, and students who have access to these tools build critical skills needed for their future careers. (Papanastasiou et al., 2019). Virtual learning environments have also been shown to offer a way to provide students with meaningful, relevant, industrial experience (Maynard et al., 2012).

As well as providing students with authentic and industry-relevant experience and skills, AR and VR can address the challenges of cost and accessibility associated with traditional physical pilot plants. They can substitute, augment and supplement hands-on experience and provide a more inclusive learning environment that is accessible remotely and simultaneously by an almost infinite number of students. For those who do have direct access to the physical apparatus, the option to precede or repeat a physical activity in a virtual environment offers students the opportunity to consolidate their learning from the lab activity and gain a deeper understanding of the underlying principles and processes by allowing them to explore beyond the equipment's physical and safety limits. Activity development using AR and VR can be simplified, and the scope of activities broadened. Instructors no longer need to apply rigorous safety standards and multiple pre-delivery tests of the methods. Students can also develop their own experiences and freely explore scenarios without prescriptive instructions. AR and VR can also be used to simulate online process upsets during an activity, adding authenticity to the experience and building the students' ability to troubleshoot and make informed decisions in a controlled but flexible environment.

The use of AR and VR to enhance and complement pilot plant experiences in tertiary education is increasing, and there are potentially significant benefits to student learning and experience. For example, Díaz et al. (2023) showed that a combination of AR and physical apparatus helped students to understand the concepts and equipment operating procedures for distillation, heat exchanger, and flow apparatus. Motejlek and Alpay (2023) showed that both the VR and multimedia-based activities lead to comparable data retention and student self-efficacy. Carberry et al. (2023) showed that the development of critical practical skills such as basic familiarity, operating and reporting is possible using eXtended Reality solutions.

In 2022, Monash University Faculty of Engineering installed and commissioned the Monash Membrane Pilot Plant (Figure 1). The apparatus is currently used in first-, second-, and third-year coursework units to enable chemical and civil engineering students to apply theory to practice in the real-world context of a common industrial process. To enhance the student experience and provide graduates with necessary digital skills, we are developing AR and VR applications to support and complement the physical pilot plant and enhance the students' capabilities by providing additional pre- and post-lab activities.

THE MONASH MEMBRANE PILOT PLANT

The Monash Membrane Pilot Plant (Figure 1) is a semi-industrial scale membrane-based process capable of removing contaminants or recovering products from water using ultrafiltration and reverse osmosis technologies. The Monash Pilot Plant includes many common unit operations, such as tanks, pumps, and heat exchangers, as well as the membrane modules themselves. The plant also includes many other components that would be present in an industrial processing plant, such as sensors, valves, safety elements, and an automated control system. This design gives undergraduate engineering students the opportunity to gain practical experience with a real-world process.

Figure 1. The Monash Membrane Pilot Plant

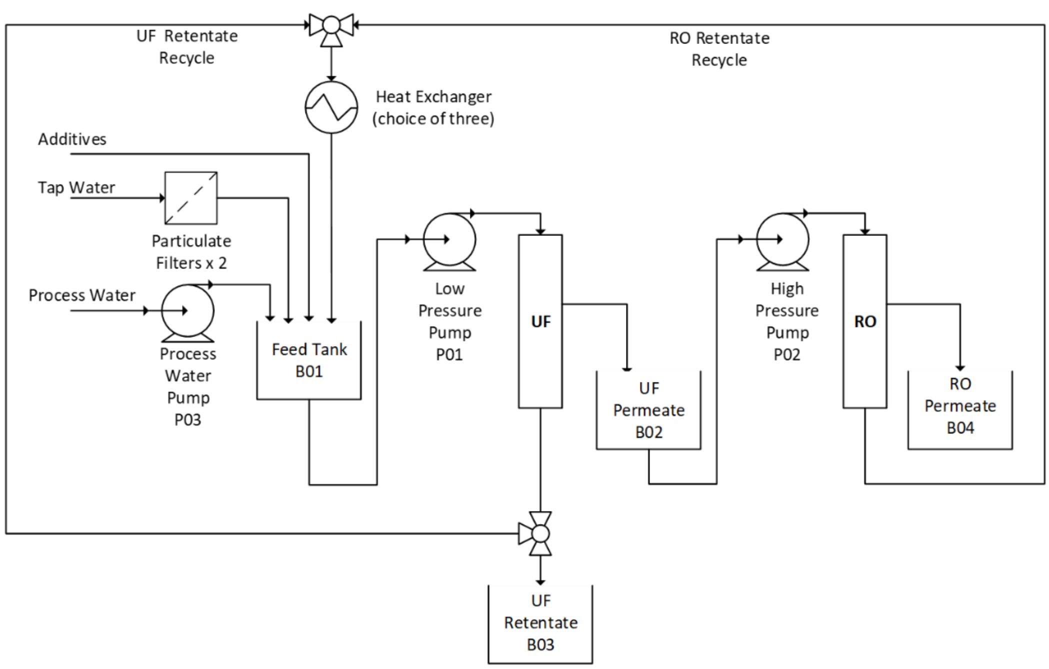

Figure 2. Schematic representation of the integrated UF/RO process

The process consists of two integrated treatment circuits (Figure 2): a low-pressure ultrafiltration (UF) circuit and a high-pressure reverse osmosis (RO) circuit. The process is semi-continuous, with a buffer tank between the two circuits to manage the differences in pressure and flow. The UF circuit is semi-automated, with flow and pressure control loops and an automated clean in place (CIP) backwash system. The RO circuit is controlled manually. Both UF and RO circuits can be run in retentate collection or concentration modes, depending on retentate recycle back to the feed tank is desired. When the circuits run in recycle mode, the retentate stream gains heat from the pumps. The heat is removed by the heat exchangers to keep the feed temperature constant and minimise viscosity effects on the membrane flux and separation efficiency. There are three different formats of heat exchangers available to remove heat from the UF/RO retentate recycle stream: plate, annular and coil.

The Monash Membrane Pilot Plant is currently used to deliver laboratory activities that enable students to connect theory to practice in eight coursework units in years one, two and three of their undergraduate courses. The activities are designed in a scaffolded manner to encourage students to build upon their prior experience and knowledge of the apparatus when returning to the pilot plant to undertake more complex and open-ended activities later in their courses. In our common first year unit, Engineering Design, students undertake basic orientation and familiarisation activities such as line tracing and development of engineering drawings of the pilot plant process. In second year, students conduct hands on experiments related to core discipline-specific units (heat and mass transfer, thermodynamics) in chemical and environmental engineering by following a laboratory manual with detailed instructions. In third year, students in chemical engineering are given simpler instructions and asked to conduct step testing on the pilot plant control loops to generate data with which they can create simple linear models that represent the pilot plant process dynamics. For each of these apparatus-based activities, we are developing supporting AR and VR activities to enhance the authenticity and learning outcomes for students.

CDIO APPROACH

We have adopted an iterative process to develop new pilot plant activities based on the CDIO approach. The Director and Monash Pilot Processes Team **conceive** new pilot plant teaching activities by working with unit coordinators and subject matter experts to identify opportunities to use the pilot plant to demonstrate an engineering concept, skill, or competency. The same group then **designs** an activity that enables students to build on and apply their prior knowledge, both theoretical and practical, to meet the learning outcomes of the activity and the unit. We pre-test and **implement** the new activities and collect in person feedback from staff and students with which to iterate and improve the content and delivery in the same semester. We have now been **operating** pilot plant teaching activities for four semesters and have received overwhelmingly positive anecdotal feedback from students and staff. We plan to start systematically generating evidence of our operations in Semester 1 2024 by collecting reflections from students and staff for each of the coursework units in which the pilot plant is used.

Students were and are deliberately involved in every step of the implementation of the pilot plant from commissioning to maintenance and operation to delivery of teaching activities. The original pilot plant process design was based on work conducted by two Master students in 2020. The Monash Pilot Processes (MPP) Student Team assisted with commissioning and are now actively involved in educational development and delivery. This ensures that we are not only adopting the CDIO approach to develop new educational activities, but we are also training students in the CDIO approach. These students will therefore benefit both during their tenure as student team members and pilot plant demonstrators, but also in their future careers.

Pedagogical Frameworks and CDIO Standards

The adoption of AR and VR in tertiary education aligns with established pedagogical frameworks that emphasize interactive and student-centred learning. We typically take a constructivist approach and apply experiential learning theory as well as CDIO Standards 5, 7 and 8 when developing our AR and VR pilot plant activities. Both frameworks highlight the importance of students actively participating in their learning through simulations, projects, and hands-on activities.

The constructivist approach emphasizes active engagement and hands-on experiences and shows strong evidence of effectiveness in engineering education (Soliman et al., 2021) and aligns well with CDIO Standard 5, which focuses on design-implement experiences. Both stress the importance of students actively participating in the process of developing products, processes, systems, and services. AR and VR applications help facilitate this constructive learning process by providing students with simulated environments and interactive elements. Additionally, it resonates with CDIO Standard 7, promoting integrated learning experiences that combine disciplinary knowledge with personal and interpersonal skills. The constructivist approach also supports CDIO Standard 8, as it inherently fosters active learning through engagement in manipulative, analytical, evaluative, and applicative activities.

Experiential Learning Theory (ELT) underscores the importance of learning through reflection on experiences (Kolb et al., 2001) and has been successfully applied to the use of AR to enhance laboratory activities. For example, Abdulwahed and Nagy (2008) applied Kolb's experiential learning cycle to develop virtual lab preparation sessions that were shown to enhance the learning outcomes of students in the experimental group in comparison to the control group. ELT aligns with CDIO Standard 5, emphasizes learning through concrete experiences and active experimentation in design-implement experiences. It supports CDIO Standard 7 by combining disciplinary knowledge with personal and interpersonal skills. Experiential Learning Theory aligns with CDIO Standard 8 by promoting active engagement and reflection as integral parts of the learning process. Many of our AR and VR activities also draw upon previous experience of CDIO implementation for similar activities at other institutions, as presented in the following section.

PILOT PLANT DIGITAL ACTIVITY DEVELOPMENT

AR Experience

The AR experience is a simple offline experience that has been programmed in Vuforia Studio (PTC, 2024) and is accessible by students via the Vuforia View app on their phone or tablet. The app allows students to view a scalable 3D render of the pilot plant overlaid onto their current physical environment. They can 'walk around' the pilot plant, zoom in, and select items to toggle text box popups (if enabled) with more information about that part of the pilot plant. Undergraduate engineering students use the AR experience up to two times in their course, depending on their discipline.

In our common first year unit, Engineering Design, students undertake basic orientation and familiarisation activities such as line tracing and development of engineering drawings of the pilot plant process. Cheah (2021) reported that students were able to effectively learn how to line trace and draw a P&ID based on a physical pilot plant. In our activity, due to the large cohort size, we provide students with an AR version of the pilot plant (Figure 3) for the same purposes.

We also provide the same AR experience to second year students undertaking an activity to assess the steady state heat transfer rate and overall heat transfer coefficient of two different heat exchangers on the pilot plant. Students are required to complete two pre-lab activities using the offline AR experience: 1) complete a P&ID labelling exercise to ensure they are familiar with the parts of the pilot plant that are relevant to the activity they will complete 2) complete a safety quiz based on the AR experience and a short supporting video. The use of AR and VR in this scaffolded manner and for safety purposes has been previously reported to be successful (Katerina Yang, 2020) and we have observed comparable results. Students who have completed the first-year activity are able to complete the second-year activities more quickly and with greater accuracy, and they have a greater understanding of and appreciation for the safety considerations of operating the pilot plant.

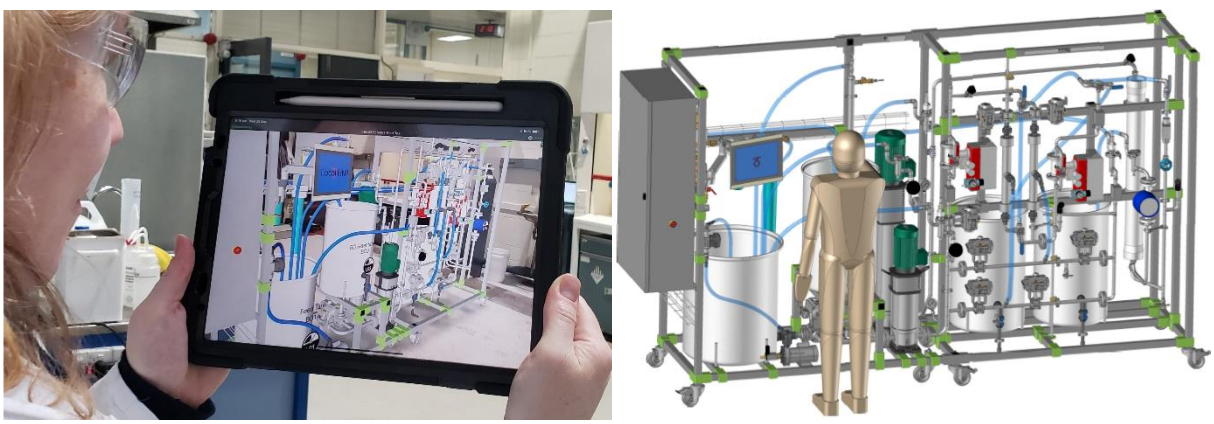

Figure 3: The AR Experience in Vuforia View, and the 3D render of the pilot plant

VR Experience

The VR experience is being developed by Monash Pilot Processes for operator training and student activities. It is an immersive simulation of the pilot plant and its surrounding environment. This program is intended for use with mixed reality devices, such as the Microsoft HoloLens, where the user is part of in the virtual environment, receiving and responding to in-experience instructions and online or simulated responses based on their interaction with the model. The VR experience can also be run on a PC as an AR experience in cases of user preference or low availability of VR hardware. The instructions displayed to the user at a given time are determined by a state machine which tracks the simulation as it is computed. Currently this state machine is manually designed, but future work aims to leverage the knowledge graph to streamline the creation of training experiences.

We are using the Unity Real-Time Development Platform with Vuforia Engine for virtual / augmented reality functionality. Previous applications of Unity for AR/VR following the CDIO approach have recently been reported (Ivanna Sandyk, 2023). We use Protégé for ontology definition, and a Python script to generate the individual nodes and relationships of the graph which adhere to this ontology. The simulation underpinning the experience operates on a knowledge graph which encapsulates information about the plant for use in different contexts. The knowledge graph contains information about the different devices (pumps, tanks, sensors, valves, heat exchangers) which are part of the plant. Knowledge graph-based simulation was chosen as it explicitly separates the representation of the structure of the process from how it is to be modelled. This allows more freedom in application than if the two were coupled. For example, an activity might involve substituting different membrane models to compare their ability to capture phenomena seen in membrane separations.

The experience is currently configured as an operator training experience, the user can carry out a set experimental procedure, following instructions as they are given by the program. Figure 4 shows the simulation environment and example instructions that the user is given to operate the model pilot plant. Rather than being an authored sequence of steps, the behaviour of the simulation is the result of a self-consistent set of rules, with the intent that the user be able to push the limits of the simulated process as bounded by those rules, approaching, and even surpassing the capabilities of the physical pilot plant. More open-ended educational activities can be designed by taking advantage of this. For example, tasking students with achieving a given yield despite malfunction in a particular sensor, requiring them to draw on a more holistic understanding of the process and the phenomena at play. This will enable students to move towards CDIO Standard 5.

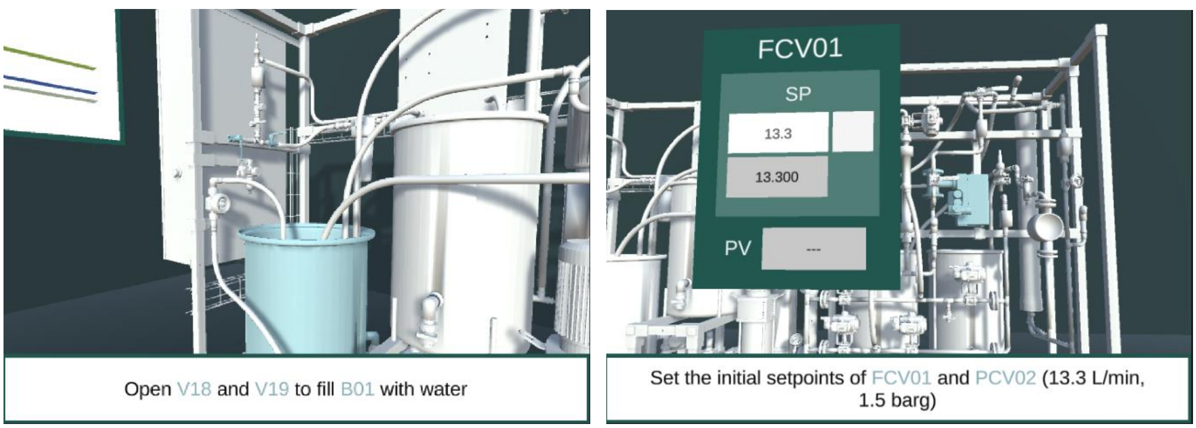

Figure 4: The VR Experience in Vuforia Engine showing text instruction and highlighting of the relevant parts of the simulation for user interaction.

RESEARCH PLAN

The past two years have been focussed on commissioning the physical pilot plant and developing the AR and VR experiences. We are now operating and ready to implement and our interventions and design methodologies and methods to collect evidence of their efficacy.

We believe that the implementation of AR and VR experiences to support and complement pilot plant labs improves the student experience and achievement of intended learning outcomes. We aim to show that students' achievement of the learning outcomes (as indicated by their unit grades) is positively affected by our interventions by comparing 2024 student grades with those of past cohorts in the same activities in the same units. CDIO literature indicates that this may be the case (Jörg Schminder, 2019). We also aim to show that student cognition develops towards higher levels as they undertake the scaffolded physical and digital Pilot Plant activities by analysing student and staff reflections for students at different year levels.

We are constructing a mixed methods research design to collect evidence to test the above hypotheses including:

- Pre- and post-analysis of student reflections on their experience in pilot plant activities
- Multi-year, cohort specific analysis as well as generalised year level analysis, including grade analysis to determine the impact on student performance
- Standard university-run student satisfaction surveys, which include quantitative and qualitative questions related to the standard of the unit.

We already know that the Pilot Plant improves the undergraduate student lab experience based on early, informal student feedback. We will develop and validate tailored pre- and post-survey instruments and reflective activities to collect the data. The instrument will include several Likert-style questions to probe specific points of interest, as well as a reflective section that will be used to track the development of student learning as indicated by the students' use of Taxonomy words in their reflections, or by derivation of the Taxonomy levels from the students' reflections. We will also be looking at the scaffolded activities and student development through the year levels through a systems thinking framework whereby students develop the ability to make sense of complex situations of scenarios, including industrially relevant wicked problems, in terms of a structured whole consisting of related internal and external elements.

We are currently in the process of refining the methodology and combination of methods and relevant instruments that will be applied in this research and will shortly be applying for ethics approval to enable us to validate the instruments into the Pilot Plant physical and digital activities in Semester 2 2024, and conduct comprehensive evaluation of our interventions in 2025.

CONCLUSION

AR and VR experiences can significantly improve accessibility and learning outcomes associated with practical activities in undergraduate engineering courses. Monash University Faculty of Engineering are developing digital activities using the CDIO approach to enhance and complement our physical pilot plant activities, which are scaffolded across the first three years of the undergraduate engineering course. We have implemented AR experiences based on an offline 3D model of our pilot plant for first- and second-year students to provide orientation and familiarisation with the equipment, safety training prior to hands-on activities, and the opportunity to apply theory to practice in creating and interpreting engineering drawings. Anecdotal feedback indicates that lab activities where physical apparatus is supplemented by an AR experience, either prior to or post lab, deliver an improved student experience. We are currently designing an immersive VR experience with a comprehensive dynamic model of the pilot plant. The VR experience will enable user interaction and facilitate improved access to the equipment for training and coursework activities, including the ability to operate scenarios that are beyond the physical or safety limitations of the pilot plant itself. The next steps for this project are to complete the activity design and implementation, and to collect evidence of the efficacy of our project to improve intended learning outcomes for students using the pilot plant and its associated AR/VR experiences.

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BIOGRAPHICAL INFORMATION

Isuru Peiris is an undergraduate student at Monash University, pursuing a bachelor's degree in electrical and computer systems engineering and arts. As Digitalisation Lead for the pilot processes, Isuru is developing tools to assist operators and engineers working with the team's wastewater treatment pilot plant and looking for ways to extend or scale successes beyond the pilot scale.

Dr Joanne Tanner completed her bachelor's degree in chemistry and chemical engineering at Monash University in 2008. She went on to gain industry experience in control systems design and configuration during her role at Honeywell, and subsequently managed and implemented client-driven chemical engineering research projects at laboratory, pilot, and industrial scale with HRL Technology. She returned to Monash and completed her PhD in reaction engineering. She has designed, commissioned, and demonstrated several fit-for-purpose, pilot scale reactors and her current research interests include reaction intensification via microfluidic reactors, and resource recovery and biorefinery for sustainable fuel and chemicals production. Joanne is currently a senior teaching fellow in the Faculty of Engineering at Monash University, with a focus on enhancing engineering laboratory experiences for undergraduate and postgraduate engineering students. She is the Director of the Monash Pilot Plant. Her teaching and research interests include sustainable processing, biorefinery, digitalisation in chemical engineering, and the use of pilot scale equipment and processes to enhance engineering education.

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