MixedLAB: Mixed Reality to Teach Students Experimental Knowledge in Microfabrication

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ABSTRACT

We are developing a new approach to leverage Mixed Reality (MR) affordances for teaching microfabrication processes, such as performed in a cleanroom. Our goal is to design interactive MR content to improve microfabrication and cleanroom training practices. MR presents a promising avenue as it allows hands-free interaction with the system and diminishes cognitive load when learning complex content. We incorporate diverse learning techniques such as real-time feedback, scaffolding, simulations,

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inquiries, and multimodal interactions to enhance the efficacy and feasibility of educational practices in the design of applications. In a course about microfabrication in bachelor curriculum, we carried out hands-on training sessions in a real cleanroom environment. By the end of the course, five students completed their experiments. We observed that MR was effective in customizing learning experiences and increasing student engagement. Additionally, MR proved helpful for teaching assistants in clarifying complex concepts and phenomena related to the fabrication tools during practical sessions. Although the small sample size limits our ability to draw definitive conclusions, initial qualitative assessments and post-training evaluations suggest that integrating MR into practical engineering education holds great promise.

1 INTRODUCTION

1.1 Background

Learning microtechnology/nanotechnology (Micro/Nano-tech) can be difficult because of its multi- and interdisciplinary nature (i.e., a mixture of biology, physics, math, chemistry, and engineering). Microfabrication faces complicated teaching and learning problems. There is a significant demand in well-trained workforce, yet educational institutions often lack the necessary infrastructure. Students find it difficult to integrate knowledge from these diverse fields and to apply it to the ‘invisible’ micro-scale. Many are hesitant to operate in laboratory settings due to the intricacies involved. Microfabrication not only demands a grasp of these foundational concepts but also the development of practical skills through hands-on laboratory experiences. However, equipping a lab with the required facilities, including a cleanroom, alongside ensuring safety training and the availability of skilled personnel, poses its own set of challenges.

1.2 Literature Review

Extended reality (XR) is growing rapidly in a range of industries and education (Fortman and Quintana 2023). XR is the overarching term that encapsulates current and future development in virtual reality (VR), augmented reality (AR), and mixed reality (MR) (Logeswaran et al. 2021). The application of XR in engineering and STEM education is increasingly diverse and impactful. For instance, AR has been effectively utilized in chemistry lab experiments to enhance learning and training (Chen and Liu 2020), (Dinc et al. 2021), (Domínguez Alfaro et al. 2022). Besides, AR also has the potential to make abstract concepts more tangible, as demonstrated in physics (Radu et al. 2023), (Radu and Schneider 2019), or bioscience education (Reeves et al. 2021). In the context of VR education, VR supports mathematics education through embodied learning mechanisms, enhancing students' engagement and understanding (Chatain et al. 2023), problem-solving skills (Halabi 2020), etc. MR has been shown to improve learning outcomes across various STEM subjects, offering interactive and immersive experiences. In the field of microfabrication specifically, research is currently more limited but still noteworthy. For example, an accessible VR ecosystem provides immersive education in nanotechnology (Kamali-Sarvestani et al. 2020), and a recent MR application has been developed for microfluidics courses (De Micheli et al. 2022). The complex and interdisciplinary nature of microfabrication, which integrates elements of physics, chemistry, and mathematics, presents unique challenges in translating theoretical concepts into practical applications for students. XR technologies, therefore, offer promising solutions to these educational challenges by making intricate and often invisible aspects of microfabrication more accessible and understandable.

As for the pedagogical methods, mixed-method combines the qualitative and quantitative approaches to provide a comprehensive understanding (Borrego, Douglas, and Amelink 2009), which has been applied associated with XR studies (Johnson-Glenberg and Megowan-Romanowicz 2017). Additionally, core theories in learning sciences, such as Kolb's Experiential Learning Theory, emphasize the importance of hands-on training, enabling students to benefit from concrete experiences (Kolb 2014). The concept of scaffolding, introduced by Bruner, involves providing essential instructional support that gradually decreases as learners become more proficient (Bruner 2009). The use of interactive media in XR is particularly intriguing because it can dynamically and personally adjust this scaffolding. The idea of productive failure is activating the prior knowledge and attention to a hidden efficacy through the designed failures (Kapur 2008). These educational foundations have been widely applied across various topics((Fleischer et al. 2023), (Hou and Keng 2020), (Quintana et al. 2004), demonstrating their effectiveness in enhancing learning outcomes through XR technologies.

2 METHOD – APPLICATION DESIGN AND MODULES

In this practice paper, we introduce *MixedLAB*, an MR application designed to blend virtual and real environments for microfabrication learning. Unlike fully virtual simulations, *MixedLAB* complements physical experiments by bridging the gap between theory and hands-on practice. This tool allows students to visualize and understand complex processes before performing actual experiments, thereby boosting their confidence and competence.

By integrating MR tools like MixedLAB into our teaching, we preserve the irreplaceable value of tactile, hands-on learning while enhancing it with digital technology. This innovative approach promises to equip future engineers and scientists with the knowledge and skills needed to excel in an increasingly complex and interdisciplinary field.

Many MR and AR applications focus on replicating real-world interactions with high-fidelity and immersive environments. However, they often fall into the trap of emphasizing technological affordances over the student’s learning experience. To avoid this, we began our project design by conducting interviews and semi-structured investigations among students learning microfabrication. This helped us ensure that our design meets the real needs of students.

MixedLAB, designed for MR headsets like the HoloLens (Microsoft), utilizes the Microsoft Mixed Reality Toolkit (MRTK) to support specific learning scenarios in microfabrication. It offers a set of experiences that supplement the practical modules assigned by educators, with each module focusing on a specific skill or knowledge area in microfabrication. Additionally, the system's content can be customized for other subjects, making it versatile for broader educational applications. To address the high development costs of AR within Unity, we created an administrative platform that allows teachers to modify content, significantly reducing future development time and costs.

2.1 Description of *MixedLAB*

The present study applies a co-design methodology (Sanders and Stappers 2008), which invites the stakeholders into the design process, including teachers, researchers, and students.

The iterative process began with the definition of the educational need, which is to better teach students experimental knowledge with a deeper understanding. Besides, after the co-design process, we selected several topics that are fundamental and challenging since they require both theoretical knowledge and experimental experience. Subsequently, a low-fidelity prototype was created and evaluated. For this process, 8 students and researchers in engineering participated in a think-out-loud study and completed usability questionnaires. The think-out-loud process helped define problems in the first version such as no direct feedback and response after interacting with buttons, voice inputs are not intuitive, etc.

It is worth noting that after the first pilot study, we found that several topics such as photolithography in microfabrication are suitable for MR learning. This topic was chosen in the case study as it is one of the typical and fundamental experiments done repeatedly in introductory courses of both undergraduate and graduate curricula. Furthermore, students struggle to understand the phenomena and reactions during the fabrication process while operating advanced equipment because of the lack of visibility.

2.2 Application Design Principles

Figure 1 displays different screenshots from *MixedLAB's* learning modules. These codes, integral to physical, real-world scenarios, allow for an overlay of digital information, like visualizations and auditory feedback, directly onto actual experiences. When participants scan a placed QR code, *MixedLAB* guides them through relevant learning modules, such as substrate pre-treatment steps. The subsequent paragraphs will delve into how the application, adhering to essential learning science principles, was developed:

Scaffolding: The term "scaffolding" is used in learning science to refer to support designed to help participants learn productively in problem-solving contexts (Fischer 2018). We designed virtual representations that gradually display and support participants from different perspectives. For example, to help students understand why Hexamethyldisilane (HMDS) treatment does not work on chromium surfaces, we start by zooming in to show 3D structures of molecules at the nanoscopic level. Finally, we conclude and guide them through the experimental processes (Figure 1. a, b).

Real-time feedback: In practices, it is common that one teaching assistant (TA) needs to coach students in a group, which results in neglecting individual students' needs and questions. However, the idea of *MixedLAB* is as participants engage in tasks, they receive immediate, contextual information about their actions. For instance, if a student makes a mistake, the system guides him/her to understand and correct it. This instantaneous feedback ensures that all the participants are engaged and learn through the interactive representations (Figure 1. c).

Personalized learning trajectory: In *MixedLAB*, personalized learning trajectory tailors the educational experience to each participant's unique needs and learning speed in the MR affordances. It accommodates different learning styles and speeds, making the study of experimental practices more efficient and effective, as students can better focus on what they need for their improvement. At the same time, the system tracks students' performance data such as their attempts on questions, time spent on the single questions, etc. Researchers can analyze students' log data to adapt to the level of difficulties and problems students mostly struggle with (Figure 1. d).

Reward system of gamification: Incorporating a rewarding system of gamification into the application enhances engagement and motivation in learning and has been used a lot in XR educational applications (Díaz et al. 2019). We applied a reward system to the questions to encourage students to answer the questions quickly and correctly. The participants' initial attempts at the task will be recorded. If they answer correctly within the allotted time, they will earn a golden coin. However, if they answer after the time limit, they will receive a silver coin instead. In this case, students are still allowed to explore different options but still get rewards for performances. This gamified approach makes the learning process more enjoyable and stimulating, encouraging continuous participation and effort (Figure 1. c).

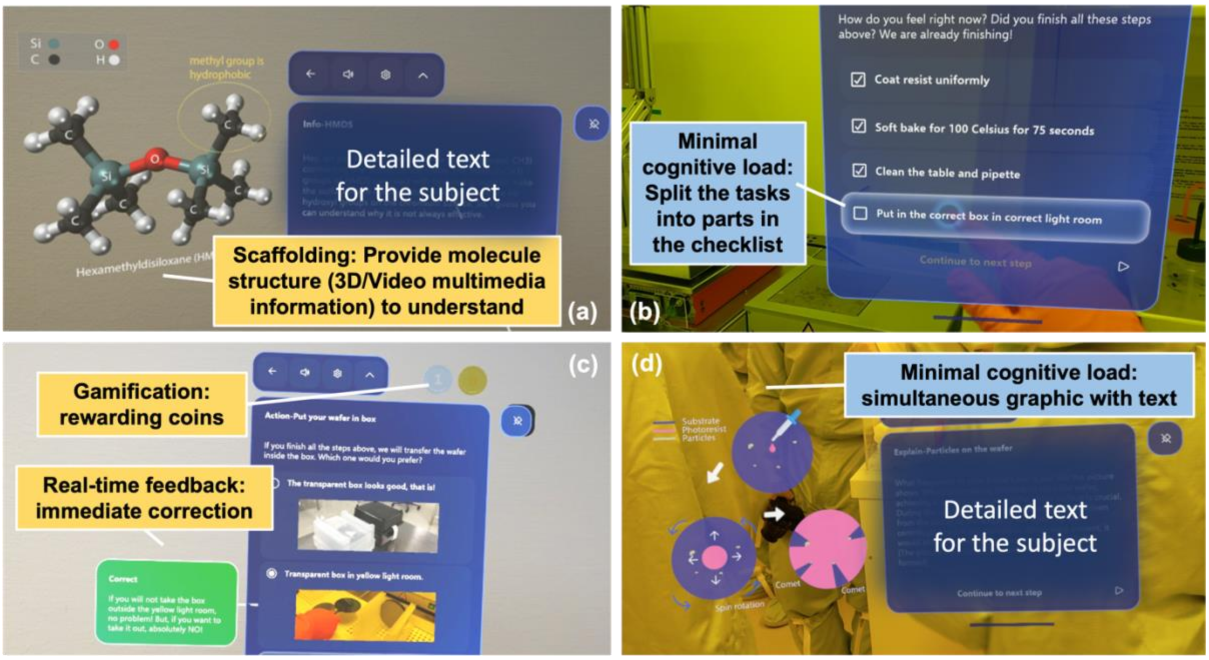

Figure 1. First-person engagement with different design functionalities inside the MixedLAB application: (a) While learning pre-treatment in photolithography, it provides 3D model representations to display the reactions behind the theory. (b) A screenshot of the spin coating module process flows to finish the steps, which reminds participants to check their process and "check" virtually on the button. (c) A screenshot of real-time feedback and reward coins from the integrated quizzes. (d) A screenshot after selecting wrongly in the previous quiz step, a further explanation with simultaneous graphics and text are displayed.

3 METHOD – APPLICATION DESIGN AND MODULES

3.1 Participants and Curriculum

Once the Human Research Ethics Committee approved our proposed experiment (No: HREC000439), we invited undergraduate students to enrol in the practical course for microfabrication. Eight of the twelve undergraduate students participated in the experiment voluntarily ($N_{class}=12$, $N_{MR}=8$). The students were invited to take part in the pre-training for HoloLens one week before the experiment. Each participant spent around 30 minutes on the 'playground' designed for them in the same *MixedLAB* application to get familiar with the basic functions. No participant reported their discomfort during the pre-training. Ultimately, five students were able to conduct the experiments due to scheduling conflicts. We obtained their consent before participation and assigned each a code to anonymously track their performance via the application. It is important to note that this performance tracking did not affect their official course grades, and no personal information was required to ensure anonymity. The entire process is illustrated in Figure 2.

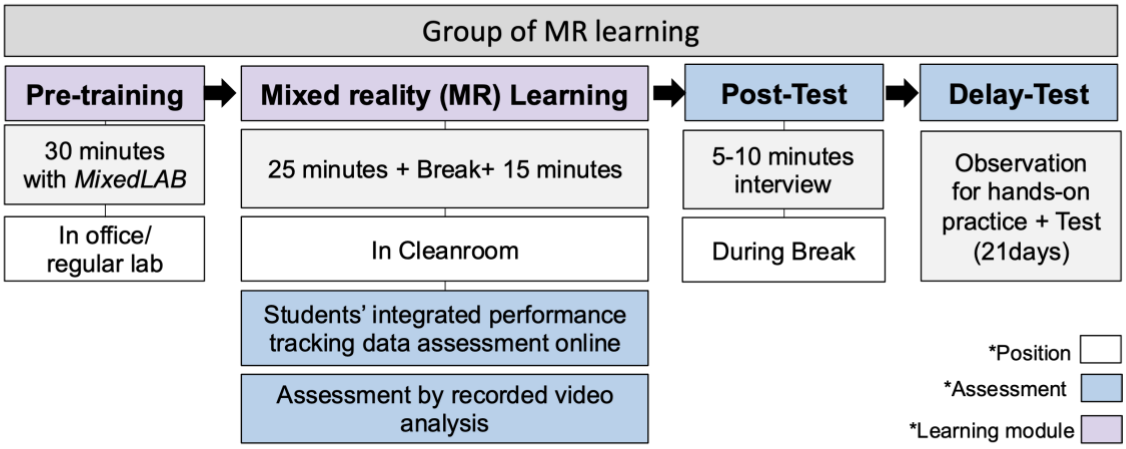

Figure 2. Process flow of participation

3.2 Results and Discussion

Because of the low number targeted participants, we did not take the between-subjects comparison to split the volunteers into two conditions. Instead, we calculated the NASA Task Load Index (TLX) (Hart and Staveland 1988) cognitive load of MR condition and Non-MR condition by within-group comparison in Figure 3. Although the result is not significant, we can still extract that it is slightly more physically demanding, and mentally demanding in MR condition. On the other hand, it is less temporal demanding, less frustrating, less stressful, and requires less effort but with higher successful performance.

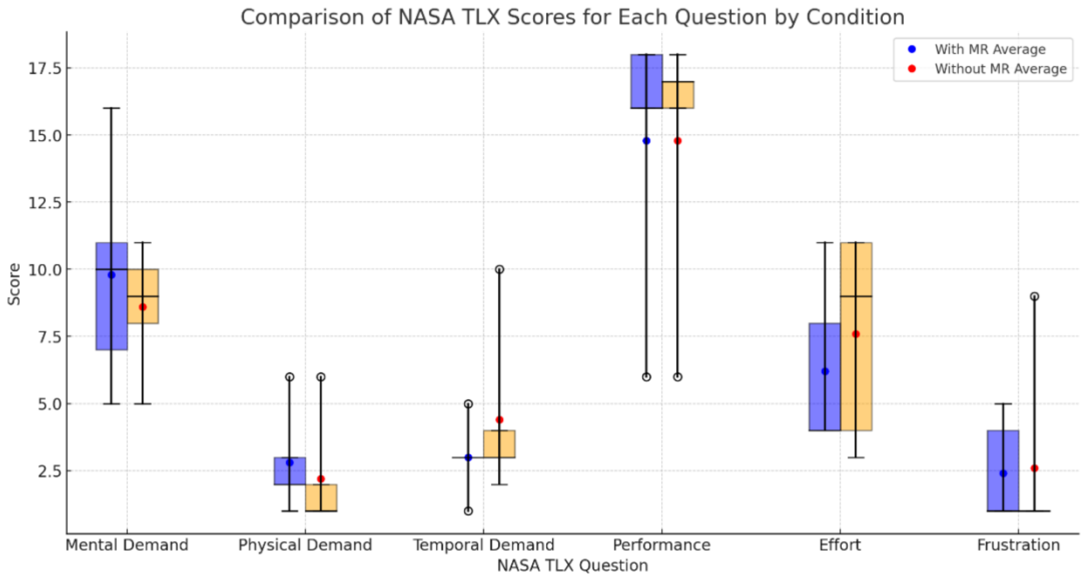

Figure 3. NASA TLS comparison between two conditions: students performed experiment with MR and then tested their knowledge without MR in the same environment after 21 days

In Table 1, We conducted semi-structured interviews with the students (see Table 1) to help researchers better understand which features of MR in engineering education students enjoyed. And those quotes are selected removing "no comments" and redundant feedback. From the table, we could interpret that students benefit from practical learning, personalized learning, interactions, etc. Also, we could see that experimenting with MR is unexpectedly natural and presenting differently compared with the classroom. As Figure 4 and Figure 5 depict that students are working individually with virtual guidance, this also coincides with their qualitative feedback (as P4 says).

Table 1. Feedback from students with semi-structure interview

Questions	Code	Voice answers transcripts
How do you feel after a mixed reality experience?	P3	"It is fun, it is really good, and it **changes from the classroom**."
	P1	"It is **natural**, actually I **can't really feel it**, I know where is dangerous and this makes me **feel safe**."
	P2	"In general, I am feeling good and it's **really fun**…"
What is the good part of the *MixedLAB* application for you?	P2	"I like it when you have the video **presenting something wrong** with sound effects that is bad (subsequence)."
	P3	"You can **see the stuff you have to do at the same time** as what you (are) do, if you are confused at something the instructions just by your side, you don't have to do in new place, a lot of paper of stuff."
	P4	"The best thing for me is I can **learn on my own pace**, I feel comfortable when I am learning. Sometimes when I feel it is fast, I am a little bit scary to say this is too fast so I missed a bit of something. But with HoloLens (*MixedLAB*), I wouldn't be because it was so interesting and I would like to know all the details provided…… I was swimming in it."
	P5	"At first, **I didn't expect this work well on me**… But, I can really learn practices that is not included in the classroom through this … I want to learn something practical, this could be good."
What do you think of the system embedded in practical teaching?	T1	"For me, it **saves a lot of energy and time**, I also joined the design so I know for those procedures I just need to observe the students' performances and focusing more on answering their creative questions, and check if they are making any serious mistakes…"
*T is the general code for teaching assistant, and *P is the general code for participants		

Fig. 4. A group of students learn and interact with MixedLAB individually

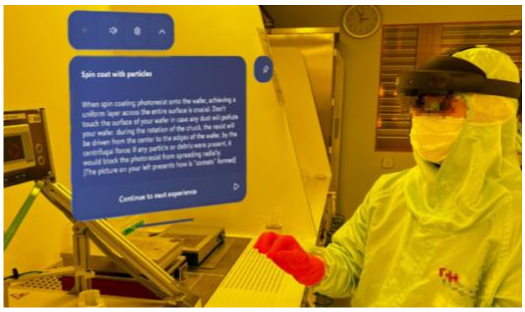

Fig. 5. Hands-free engagement with the digital panel in the cleanroom

4 SUMMARY AND OUTLOOK

In this paper, we introduced MR in engineering education, specifically microfabrication, and conducted a practice course with a small group of students. Due to the limited number of participants, we cannot state any certain conclusion. However, this practice paper allows us to explore more on the affordances provided by MR and conclude the efficient design principles and learning science principles that are aligned with them. Specifically, students enjoyed the personalized learning trajectory, the multi-media scaffolding compared to how they learn in class. The MR seems to work well if designed properly to guide them with scaffolds and experimental knowledge such as potential risks and failure, correct process, and various TA's experience. We can also conclude that students feel engaged with the MR tool while doing their experiment and it is a unique opportunity for students to bridge practical and theory simultaneously. We encourage to apply MR-assisted learning in practical experiments when students know they are safe in the environment and the instructions can be designed to distinguish virtualism and reality. Through qualitative analysis, it is worth knowing that for some subjects personalized MR-assisted learning could trigger higher confidence and achievement.

Besides, by reducing the time and effort required for TAs to provide individualized support, MR allows for more efficient and effective instructional practices. It would be promising to see whether MR enables TAs to focus more on direct interaction with students, offering timely feedback and guidance. Additionally, it is worth examining if students receive better support and personalized attention, enhancing their understanding and engagement.

Inspired by this study, we will follow up with a subsequent phase study focusing on how embodiment affects students' learning outcomes with MR, especially for conceptual understanding. Also, we will focus more on TAs' responses and tiredness while collaborating with MR tools. Ultimately, we aim to apply our concept to different experimental knowledge learning scenarios, which may lead to more efficient engineering education and science education.

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