COMPARISON BETWEEN 360-DEGREE AND DIGITAL IMMERSIVE VR-BASED TRAINING ENVIRONMENTS FOR CLEANROOM SAFETY AND FABRICATION PROCEDURES

Jordan Junior Atta Nuako, Steve Adjetey Adjei, and Michael Kozhevnikov
Norfolk State University
Norfolk, VA
j.attanuako@spartans.nsu.edu, s.a.adjei@spartans.nsu.edu, mkozhevnikov@nsu.edu

ABSTRACT

In the field of semiconductor fabrication, even when adequate training facilities are available, adherence to specific cleanroom protocols and procedures is crucial. This often leads to large amounts of training time, which can be a challenge for those with limited time or resources to attend cleanroom training physically. The noisy environment and the existence of cleaning and gowning protocols further complicate the training process. This is where immersive Virtual Reality (VR)-based training modules can be particularly effective, making a significant difference in preparing the future workforce to address these challenges. In the future, digitalization will only continue to increase, with the physical and virtual worlds connecting seamlessly via the Metaverse and Digital Twins (DT), and professions will require the use of VR tools and DT technology for their work.

This project aims to develop an immersive VR-based training module that teaches and guides users in mastering the photolithography process. For the current training module, two versions of Virtual Training Environments (VTEs) - digital-VR and 360-VR - are designed, developed, and evaluated. In digital-VR, the VTE is digitally rendered in its entirety, with 3D models created using both 3D Modeling software (e.g., Blender) and 3D Scanning techniques. 360-VR refers to 360° videos and panoramas that are first captured using professional omnidirectional cameras, which enable the filming of an entire 360 degrees, and later integrated into one of the VR development engines for further augmentation. The comparative analysis of advantages and shortcomings between digital-VR and 360-VR is conducted.

ABOUT THE AUTHORS

Jordan Junior Atta Nuako is a Process Engineer at Intel Corporation. Jordan has a master's degree in Electronics Engineering at Norfolk State University and a bachelor's degree in Telecommunication engineering, and is a member of the National Black Engineering Society.

Steve Adjetey Adjei is a Process Engineer at Intel Corporation. He received his M.Sc. degree in Electronics Engineering from Norfolk State University. Steve has a bachelor's degree in Instrumentation Engineering. His research interest is in virtual reality for nanofabrication education. He is a member of the National Black Engineering Society.

Michael Kozhevnikov is an Associate Professor at the Department of Engineering, Norfolk State University, VA. Michael received his Ph.D. in Physics from Technion – Israeli Institute of Technology, Israel. Michael was a Postdoctoral Research Associate in the Division of Engineering and Applied Sciences at Harvard University, Cambridge, MA, and a postdoctoral fellow in the Department of Electrical and Computer Engineering at the University of California, Santa Barbara, CA. Michael previously held a position as a Member of Technical Staff at Bell Laboratories, Lucent Technologies, Murray Hill, NJ. Michael Kozhevnikov's research interests include human-computer interaction, virtual reality and visualization, photonics and optical communications, and engineering and science education. Michael Kozhevnikov authored over 30 journal publications.

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INTRODUCTION

Traditional training methods in the NSU nanofabrication Cleanroom have long been the cornerstone of imparting essential skills and knowledge to higher education students and professionals alike. Nanofabrication cleanrooms are specialized laboratories with advanced equipment and technologies for fabricating and manipulating materials at the nanoscale (*Nanofabrication Lab, UMass Lowell*, n.d.). These controlled environments demand thorough attention to detail, strict contamination control, and precise handling of equipment and materials (see Figure 1). Any deviations from established protocols can significantly affect the quality of fabricated structures and devices (Rayser, 2019).

Figure 1. NSU Cleanroom Training Facilities

However, it is imperative to recognize that these conventional training approaches have limitations. Health concerns arise from stress and extended work periods in protective gear within the cleanroom environment. One of the foremost limitations of traditional cleanroom training is the stressful and potentially hazardous environment trainees must navigate. Additionally, extended periods of wearing specialized protective gear while in the Cleanroom can be physically and mentally taxing.

Nanofabrication encompasses complex equipment and procedures, often presenting students with formidable challenges. Traditional training methods require substantial practicum to sufficiently facilitate students in becoming acquainted with specialized tools and apparatus or recall and execute the multifaceted procedures accurately. The absence of practical training sessions poses a significant risk of damaging expensive laboratory equipment due to accidents, as trainees may need hands-on experience. As a result, students frequently require repetitive practice in the laboratory to overcome these hurdles and achieve proficiency in the nanofabrication process. This necessity for repetition often leads students to revisit the cleanroom to reinforce their understanding and skills.

To address this need, the integration of Virtual reality (VR) emerges as a beacon of promise. The concept of VR dates back to the mid-20th century, but it was in the 1990s that the first VR headsets started to gain traction (Barnard, 2024). Devices like the Sega VR and Forte VFX1 marked the early evolution of VR headsets, providing primary stereoscopic displays and head-tracking capabilities (*Sega VR*, 2025). These developments laid the foundation for the immersive experiences we enjoy today.

Immersive Virtual Reality training is increasingly adopted in various fields for its ability to simulate real-world scenarios and provide hands-on experience without the associated risks or costs. The COVID-19 pandemic accelerated the adoption of online education and training (Holton & Sandle, 2020). This technology has been applied in various engineering education and laboratory training. At the same time, the constraint about the level of immersivity represents a prominent limitation inherent in the existing practical applications of VR technologies (Grodotzki et al., 2018; Lucas & Gajjar, 2022; Makransky et al., 2019), particularly within the context of their utilization in engineering education and training. Most engineering education and laboratory training models are also limited in user engagement and interactivity (Han et al., 2023; Sepasgozar, 2020; Singh et al., 2020). Specifically, one challenge arises from the need for tailored controller customization and the use of advanced 3D scanning technology to generate content suitable for the virtual environment. Another area for improvement is the ineffective use of 3D space in immersive VR-based environments. These limitations underscore the pressing necessity for further research and development. However, the effectiveness of such training depends not only on the technology but also on how it is implemented, particularly in terms of the trainee's comfort and immersion. The spatial perspective afforded to trainees in a VR environment – whether they observe and interact from a first-person or a third-person viewpoint – can drastically alter their learning experience. As VR and Augmented Reality (AR) technologies continue to gain prominence in educational settings, addressing the level of presence, customization challenges, and content creation complexities is crucial in enhancing their efficacy as pedagogical tools, ultimately fostering a more immersive and practical learning experience within engineering education and laboratory training contexts.

PROJECT OBJECTIVE

The primary objective of this research is to conceptualize and develop a prototype Virtual Training Environment (VTE) for the photolithography process. Specifically, this research focuses on the following four main tasks:

1. Development of a prototype VTE using 360 cameras, 3D scanning techniques, 3D modeling tools, and 3D VR development engines.
2. Add interaction within the VTE by implementing Meta Quest controllers, elevating the quality and degree of user engagement.
3. Developing module activities encompassing various elements such as levels, quizzes, and animations.
4. Assessment of the user experience within the VTE, conducted in an immersive and interactive mode facilitated by VR headsets.

For the current training module, two versions of VTEs - digital-VR and 360-VR - are designed and developed. In digital-VR, the VTE is digitally rendered in its entirety, with 3D models created using both 3D Modeling software (e.g., Blender) and 3D Scanning techniques. 360-VR refers to 360° videos and panoramas that are first captured using professional omnidirectional cameras, which enable the filming of an entire 360 degrees, and later integrated into one of the VR development engines for further augmenting.

METHODOLOGY AND DESIGN

Digital-VR and 360-VR VLEs

1. Digital-VR (Computer-Generated Imagery Virtual Reality)

<u>Creation Method</u>: Fully digitally rendered environments.
<u>Tools Used</u>: 3D modeling software like Blender, 3D scanning techniques for capturing real-world objects or spaces.
<u>Output</u>: Immersive, interactive 3D environments that can be manipulated and explored freely.

2. 360-VR (360-Degree Video Virtual Reality)

Creation Method: Real-world environments captured using omnidirectional cameras.
Post-Processing: Integrated into VR engines (like Unity or Unreal Engine) for augmentation - adding interactive elements, overlays, or navigation.
Output: Realistic, immersive video-based experiences with limited interactivity compared to digital-VR.

Training Module on Photolithography

Optical lithography, or photolithography, is a photon-based process that involves projecting an image onto a photosensitive emulsion, typically a photoresist, which is applied as a coating onto a substrate, such as a silicon wafer (Naulleau, 2019). This technique utilizes the properties of light to create precise patterns on semiconductor substrates, playing a crucial role in semiconductor manufacturing and microfabrication processes. This semiconductor manufacturing process comprises multiple intricate steps that involve specialized equipment, necessitating substantial movement and spatial coordination throughout its execution. Therefore, integrating photolithography as a training module within VTE can significantly augment the realism and fidelity of interactions and movements supported within the training environment.

The initial phase of the training program encompasses safety precautions and a gowning procedure, during which students are guided through the entire process, followed by a comprehensive assessment. Depending on the performance, students can either progress to the subsequent main stage or revisit the gowning procedure. In this study, the photolithography process was consolidated into the following steps:

- Substrate preparation
- Coating the substrate with photoresist
- Soft baking the photoresist
- Aligning the mask
- Exposing the photoresist through a mask to UV light
- Post-exposure baking (hard baking)
- Developing the photoresist

Students are awarded points for accurately executing these procedures at each step. Upon completing the training, should a student achieve a score surpassing the predefined threshold, they are deemed to have completed the entire training regimen. Conversely, if students' scores fall below the set threshold, they are encouraged to recommence the training program.

Digital-VR VTE Design

The physical cleanroom is equipped with various instruments and tools for conducting experiments. To replicate the natural cleanroom environment within VTE, it is imperative to populate VTE with appropriate 3D content. Vizard is the primary VR development software for this research project. The 3D models are developed in Blender, a robust 3D modeling tool. As indicated in Figure 2, the VTE and the 3D models of the contents are imported into Vizard for development. The advancement of the Vizard platform entails the utilization of intrinsic physical principles, including gravity, the behavior of solid surfaces, and the dynamics of objects interacting within the VTE. Attempts to employ simpler, more expeditious alternatives, such as traditional 3D scanning applications, yielded different results. Substantial post-processing and repair work was required to rectify issues with the generated model, consequently diminishing the fidelity of the final model.

Additionally, the development process encompasses Python programming to integrate and tailor controllers, enhancing interactions and maneuverability within the VTE to closely resemble those experienced in a natural cleanroom environment. Training modules and their respective quizzes are created using the Vizard platform. The resulting training modules are accessible via a conventional 2D monitor and an immersive VR headset.

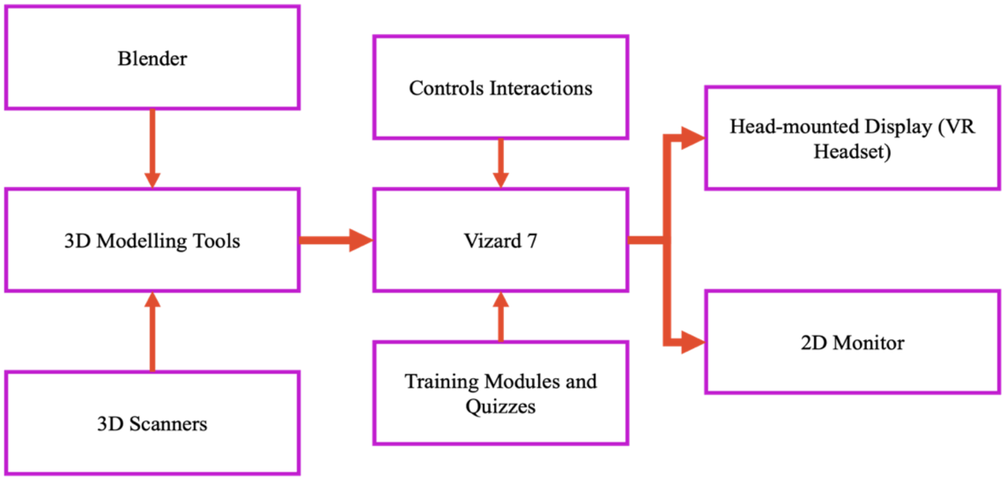

Figure 2. Digital-VR Design flow.

360-VR VTE Design

The research utilizes Insta360 Pro 2, Insta360 X3 camera, and Unity 3D development platform to create a VR training module for nanofabrication cleanroom procedures. A 360 camera, also known as an omnidirectional camera, captures a complete 360-degree view, making it ideal for tasks like panoramic photography and covering extensive visual fields ("What Is a 360 Camera?," n.d.). The use of 360 cameras in entertainment and industries like still photography and robotics has increased as virtual and augmented reality gain popularity ("What Is a 360 Camera?," n.d.). 360-VR, using 360-degree cameras like the Insta360 X3 and Insta360 Pro 2 (see Figure 3), captures real-world scenes, offering authentic experiences.

360 Camera Viewpoints

First-Person Perspective: The Insta360 X3 camera was mounted on the head (see Figure 4a) to capture the training session from a first-person perspective. This setup is intended to provide an immersive first-person viewpoint, simulating the instructor's visual perspective during the training.

Third-Person Perspective: The Insta 360 Pro 2 camera (see Figure 4b) recorded the same training session from a third-person perspective. This camera was positioned externally next to the instructor to capture a broader view of the training environment and the interactions within it.

Figure 3. The portable Insta360 X3 camera (left) and the professional Insta360 Pro 2 camera (right).

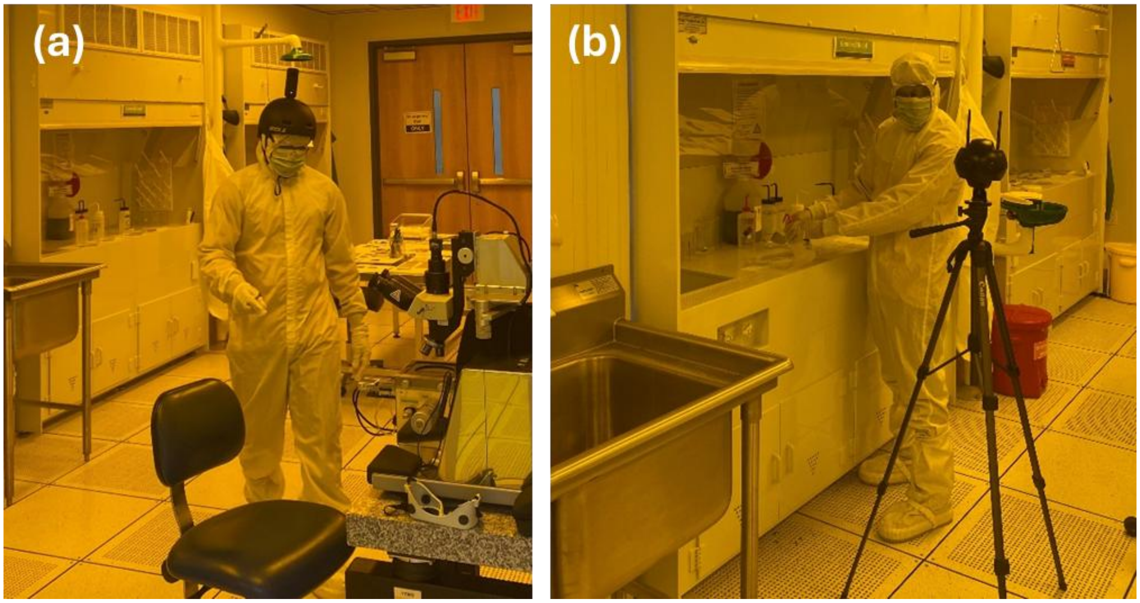

Figure 4. (a) Moving to the next location with Head-Mounted Insta360 X3, (b) Recording the substrate preparation process with insta360 Pro 2.

Unity 3D, essential for building interactive VR environments, was used in developing the training module. Unity's tools support real-time rendering, physics simulation, and VR platform compatibility. A standard training session was designed to represent typical VR training scenarios. The training session content was consistent across both recording methods to ensure comparability.

Both training sessions were recorded in their entirety using the respective camera setups. Care was taken to ensure the process and environmental conditions, such as background noise, were consistent across both sessions. The recordings were then processed and prepared for playback in a VR environment. The production flowchart is shown in Figure 5.

In addition to recording the photolithography process from the first-person and third-person perspectives, a comprehensive effort was undertaken to develop an immersive and interactive pre-training experience for trainees in a laboratory setting. The process begins by capturing the NSU cleanroom nanofabrication bays and equipment using a 360-degree video recording with the Insta360 Pro 2 camera. These visual assets are then integrated into the Unity VR toolkit to establish a realistic, engaging cleanroom environment. Remote accessibility was tested by exporting the final product to the Oculus headset. This way, the trainees could experience and navigate (by teleporting) inside the virtual photolithography room before undertaking the actual training.

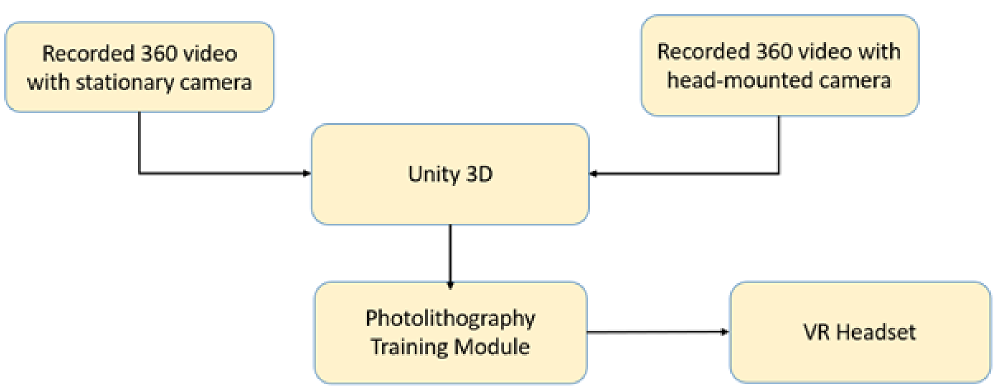

Figure 5. 3360-VR Design flow.

RESULTS

Digital-VR VTE Module

The primary objective involves recreating the NSU cleanroom within the VTE, ensuring that users' navigational experiences closely mirror those encountered in the actual cleanroom. To achieve this, acquiring the cleanroom's floor plan became vital, with precision matching between the VTE and physical cleanroom dimensions. Leveraging AutoCAD, the floor plan was carefully reconstructed to mirror the cleanroom's dimensions, improving navigation in the VTE (see Figure 6).

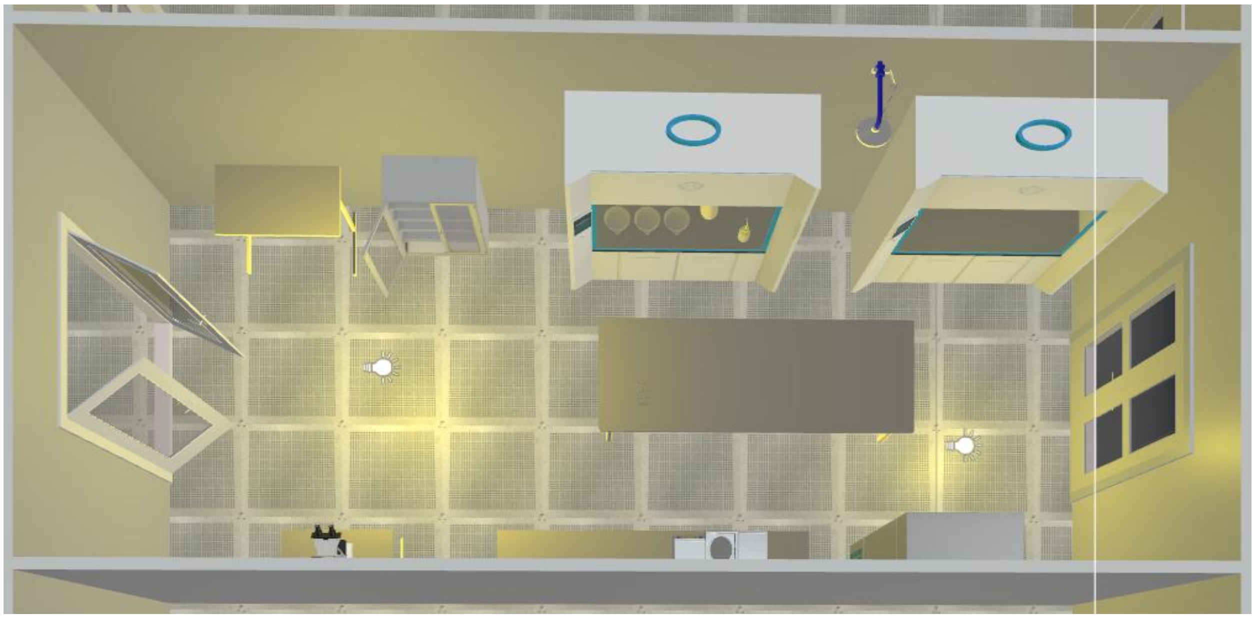

Figure 6: Photolithography Bay of NSU cleanroom modeled in Blender.

Enhanced Interaction

In the contemporary landscape of Head-Mounted Displays (HMDs), some HMDs are equipped with integrated controllers, while others lack this feature. HMDs lacking controllers are still fully functional, allowing users to immerse themselves in VR environments, albeit with limited interaction capabilities. In such cases, users primarily rely on the conventional mouse and external remote controls to navigate and engage with the VR content. This research project explores two VR headsets: the Meta Quest 3 and the Pimax 5K Super. The Meta Quest 3 is bundled with its set of controllers, while the Pimax 5K Super requires the separate purchase of its controller, the Pimax Sword, which is subsequently paired with the headset using a SteamVR base station. The comparative investigation of the Meta Quest 3 vs. Pimax 5K Super includes the analysis of the variances in their controller configurations. This comparative exploration of HMDs and controllers aims to elucidate the implications of these design choices on user engagement and interaction within virtual environments, contributing valuable insights into the environment of VR technology and its user experience.

Additionally, the current methodology tends to ignore the configurations and programming of the controllers, thus limiting the user's interaction. The controller, an extension of the human arm, has about five buttons. Each button on the controller is programmed to perform specific actions in the proposed VTE. For example, as shown in Figure 7, the index button of the right controller was programmed to grab an object if triggered.

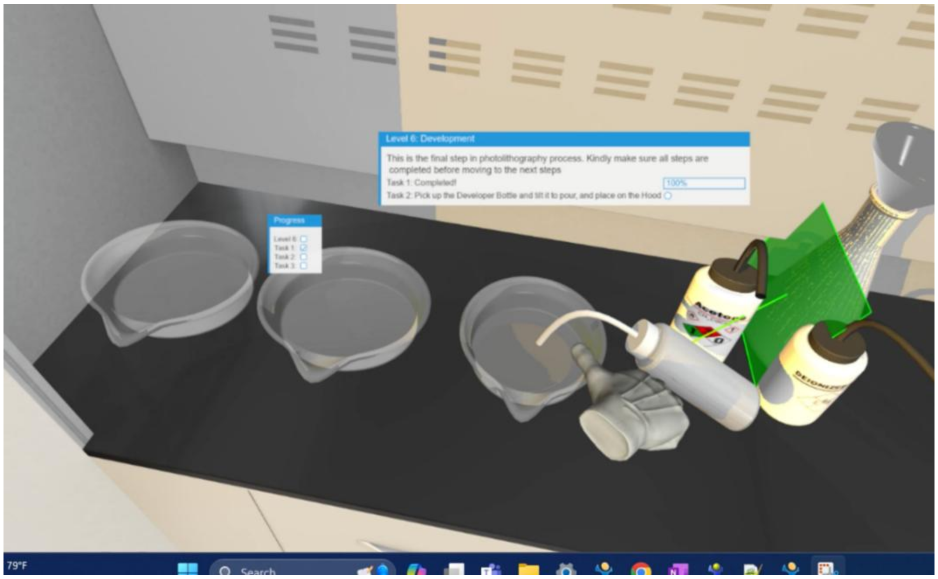

Figure 7: Using the controller to pick a bottle.

360-VR VTE Module
The study involves creating a virtual environment tailored to the training session. This environment is designed to be realistic and immersive, simulating a real-world setting relevant to the training content. The environment is consistent across both camera perspectives to ensure that any differences in participant experience were due to the perspective and not environmental variations. In both environments, the trainees can rotate their view 360 degrees by simply turning around.

Example: 360 Footage

Footage from both the Insta 360 X3 (first-person view) (see Figure 8) and Insta 360 Pro 2 (third-person view) (see Figure 9) recordings was analyzed. The footage revealed that the first-person perspective offered a more immersive and direct view of the training activities. In contrast, the third-person perspective provided a broader overview of the environment.

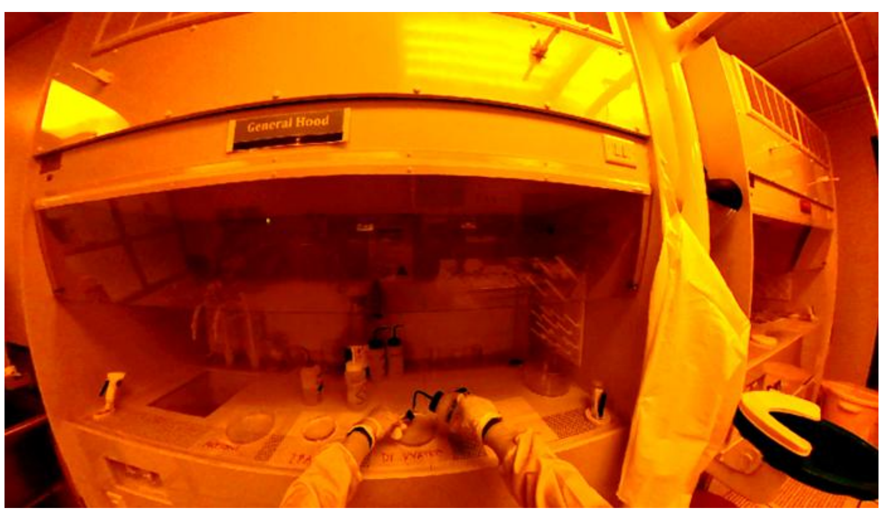

Figure 8. Sample Development Process at the Fume Hood (First-Person Perspective).

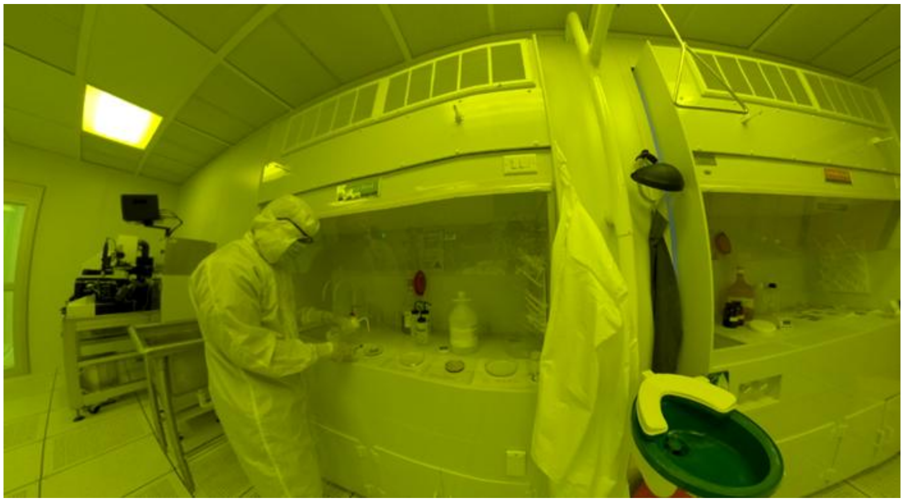

Figure 9. Sample Development Process at the Fume Hood (Third-Person Perspective).

CONCLUSIONS

In this project, two versions of VTEs, digital-VR and 360-VR, are designed and developed for the photolithography module. In digital-VR, the VTE is digitally rendered in its entirety (3D models are created using both 3D Modeling software (e.g., Blender) and 3D Scanning techniques. 360-VR refers to 360° videos and panoramas that are first captured using professional omnidirectional cameras, which enable the filming of an entire 360 degrees, and later integrated into one of the VR development engines for further augmenting.

In the digital-VR VLE module, improved realism was achieved by utilizing advanced configurations in Blender, such as the principled BSDF (Bidirectional Scattering Distribution Function), setting shadows, and incorporating proper lighting within the virtual environment. With the supported hardware and Python programming, controllers can be customized to enhance interactions (each level in the module provides different interactions). Further controller customization enabled dynamic features and navigation.

In the 360-VR VLE module, preliminary findings suggest that a dynamic first-view training experience, recorded using Insta360 X3, can enhance immersion and engagement but may also lead to discomfort in some trainees, particularly in scenarios with complex spatial navigation. Conversely, static observer positioning, recorded using Insta360 Pro 2, reduces disorientation but can lead to a less engaging experience. Regarding spatial perspective, the first-person perspective provides a more immersive experience. Still, it may increase the risk of motion sickness, while the third-person perspective enhances comfort but potentially at the cost of reduced realism and engagement.

Based on our efforts to develop the digital-VR VLE and the 360-VR VLE modules, the mapping of the main differences between digital-VR and 360-VR is summarized in Table 1.

Table 1. Mapping of the main differences between digital-VR and 360-VR

Feature/Aspect	digital-VR	360-VR
Creation Method	Fully computer-generated using 3D modeling and scanning	Captured from real-world environments using 360° cameras
Interactivity	High: Users can move freely, interact with objects	Limited: Mostly point-and-click or hotspot-based navigation
Realism	Stylized or hyper-realistic, depending on design	Photorealistic, as it uses real footage
Development Time	Longer: Requires modeling, texturing, lighting, and programming	Shorter: Faster to capture and stitch footage

Hardware Requirements	Higher: Demands more GPU/CPU for rendering	Lower: Video playback is less intensive
Flexibility	High: Easy to modify, update, or animate	Low: Changes require re-shooting
Immersion	High, especially with interactivity	High visual immersion, but limited interaction
Cost	Potentially higher due to modeling and development	Lower upfront cost, but limited scalability

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