2023 Annual Conference & Exposition
Baltimore Convention Center, MD | June 25 - 28, 2023
The Harbor of Engineering
Education for 130 Years
ASEE
Paper ID #39069

Using Virtual Reality Cleanroom Simulation in a Mixed Nanoelectronics Classroom

Sean Letavish

Sean Letavish has a BSc degree (2022) and a MSc degree (2023), both in Electrical Engineering from George Washington University. His interests lie at the intersection of virtual / augmented reality and engineering education. He has worked on a virtual reality cleanroom simulator to teach difficult concepts and skills such as nanofabrication and semiconductor manufacturing to support access and hands-on learning for a broad diversity of students and interested audiences.

Ani Meliksetyan

Ani Meliksetyan is a second-year interdisciplinary doctoral program student (Human and Technology Collaboration) at the George Washington University, Graduate School of Education and Human Development. Her research interests lie at the intersection of education technology, human-centered Artificial Intelligence and decision making, professional/adult learning, recognition of diverse forms of learning and creation of academic pathways. She envisages harnessing the power of data science and responsible use of Artificial Intelligence in education for the purpose of inviting equitable participation, creating paths to quality employment, and inducing social mobility for the most underserved.

Victoria Ravel

Victoria Ravel is an undergraduate senior biomedical engineering student at George Washington University minoring in Electrical and Computer Engineering. She has expertise in micro and nanofabrication processes.

Dr. Hurriyet Aydin Ok, GWU

Dr. Hurriyet Aydin Ok is a senior research fellow at GWU Cyber Security & Privacy Research Institute (CSPRI) and teaches courses in E-Commerce Security and Augmented and Virtual Reality. Prior to GWU, Hurriyet was a member of the IT leadership team for over 24 years at the World Bank Group, and contributed in the areas of enterprise architecture, cybersecurity, identity and access management, new technology infrastructure strategy, and IT learning and career development. Dr. Ok is the Founder of VRT-U, LLC, a startup technology venture focusing on Augmented and Virtual Reality for creating immersive learning content.

Hurriyet was a software engineer at Alcatel-Rovsing in Copenhagen, Denmark, developing software for American Airlines Data Network. Dr. Ok holds a D.Sc. Degree in Computer Science from the GWU, and M.S. and B.S. Degrees in Computer Science from Hacettepe University, Ankara, Turkey.

Dr. Natalie B. Milman, The George Washington University

Natalie B. Milman, Ph.D. is Chair of the Department of Educational Leadership and Professor of Educational Technology at The George Washington University's Graduate School of Education and Human Development. She is also a member of the interdisciplinary Human-Technology Collaborations PhD program and research lab (go.gwu.edu/htc), a member of GW's Academy of Distinguished Teachers, and winner of the 2017 Bender Teaching Award. Her research focuses on the design of instruction and models for the effective leadership and integration of technology at all academic levels; issues of diversity, inclusion, and digital equity.

Dr. Gina C. Adam, The George Washington University

Gina C. Adam is an assistant professor in the Department of Electrical and Computer Engineering at George Washington University. Apart from her work in memristive devices and circuits for novel computing, she is also interested in content knowledge acquisition in engineering education and emerging learning technologies for nanofabrication and semiconductor manufacturing.

Work-in-Progress: Using Virtual Reality Cleanroom Simulation in a Mixed Nanoelectronics Classroom

Abstract

Given the strategic importance of the semiconductor manufacturing sector and the CHIPS Act impact on microelectronics, it is more imperative than ever to train the next generation of scientists and engineers in the field. However, this is a challenging feat since nanofabrication education uses hands-on cleanroom facilities. Since cleanrooms are expensive, have access constraints due to safety concerns, and offer limited instructional space, class sizes and outreach events are limited. To complement instruction in nanotechnology education, there is some open- or educational-access software, which is computer-based and focuses only on training for individual equipment, not on the typical workflow for device fabrication. The objective of this work was to develop an accessible virtual reality ecosystem that provides an immersive education and outreach on device nanofabrication that is user-friendly for a broad range of audiences. At the George Washington University (GWU), a virtual reality cleanroom prototype has been developed. It consists of a 45-minute gameplay module that covers the process flow for the fabrication of micro-scale resistors, from sample preparation to electrical characterization.

We also performed a mixed methods study to investigate how 5 students in a nanoelectronics course utilized this virtual reality cleanroom prototype and what changes they recommend to improve its user interface and learner experience. The study population for this work-in-progress consisted of students enrolled in a nanoelectronics course at GWU during the 2022-2023 school year. Students taking this course can be undergraduate (junior or senior) or graduate (masters or PhD). The research questions for this study were 1) what is the user experience with the virtual reality cleanroom prototype, 2) what challenges, if any, did students experience, and 3) what changes did students recommend to improve the virtual reality cleanroom prototype learner experience? Preliminary results indicate that the students found the virtual reality cleanroom simulator helpful in repeatedly exploring the cleanroom space and the nanofabrication process flow in a safe way, thus developing more confidence in utilizing the actual cleanroom facility. The results of this study will provide insight on the design of future modules with more complicated levels and device process flows. Moreover, the study could inform the development of other virtual reality simulators for other lab activities. The improved usability of the proposed software could provide students in large classes or attending online programs in electrical and computer engineering, as well as K-12 students participating in nanotechnology-related outreach events, the opportunity to conduct realistic process workflows, learn first-hand about nanofabrication, and practice using a nanofabrication lab via trial and error in a safe virtual environment.

1. Introduction

The term “nanofabrication” (or nanomanufacturing) is defined by the National Nanotechnology Initiative as "the ability to fabricate, by directed or self-assembly methods, functional structures or devices at the atomic or molecular level" [1]. This requires ultra-clean facilities (cleanrooms) designed to maintain extremely low levels of dust, airborne organisms, or vaporized particles. These facilities are used for semiconductor and integrated electronics manufacturing to produce electronics such as solar panels, rechargeable batteries, displays, bioelectronic devices, etc. According to Zion Market Research [2], the global nanofabrication market is anticipated to reap earnings of about $18.69 billion by 2026.

Despite the potential earnings of this industry, the costs are also significant since cleanrooms are expensive to build, maintain, and require highly qualified personnel. The outside air entering a cleanroom has to be filtered and cooled by outdoor air handlers and the air inside is constantly recirculated and filtered to remove internally generated contaminants. The air temperature and humidity levels are tightly controlled. Special light fixtures, walls and equipment are used to minimize the generation of airborne particles. The users enter and leave through airlocks, sometimes with an air shower, and wear protective clothing such as hoods, face masks, gloves, boots, and coveralls. Cleanrooms can also have seismic base isolation systems and Faraday cages to prevent costly equipment malfunction. Nanodevices are fabricated by developing a recipe – a set of sequential steps combining multiple fabrication techniques to clean, pattern, add or remove material. This process flow requires careful and resource-consuming optimization and the use of different state-of-the-art equipment according to the fabrication technique chosen by the user, e.g. lithography, deposition, etching, etc.

This industry is constantly changing as new types of devices and processes are developed. As the fabrication techniques evolve, so does the training required for the next generation of qualified workforce needed in these nanofabrication facilities. The education and training in nanofabrication is extremely intensive since the equipment used can cost anywhere from thousands to millions of dollars. Therefore, the learning curve for this industry is incredibly steep, limiting the number of people eligible to enter this industry. The George Washington University has invested extensively by opening its Nanofabrication and Imaging Center in 2017, the GWNIC. It is an open-access core university facility with a class 100 cleanroom and an imaging suite. The GWNIC has been enhancing academic research and serving as a key site for educating the next generation of students working in this high-tech industry. Every semester there are two courses related to nanofabrication offered to local undergraduate and graduate students. However, caps on enrollment had to be imposed due to occupancy limits. Moreover, during the pandemic, the facility was not accessible for in-person student use. Therefore, the need to have an engaging alternative to nanofabrication education based on virtual reality became apparent.

Multiple studies have been conducted to determine the effectiveness of virtual reality when applied to education/training.[3] When utilized properly, virtual reality can expose users to environments they would not typically have access to, eliminate risks to their health or safety that are sometimes present in those environments, and can increase the player's motivation to learn, adapting to a wide range of learning styles.[4-5] Virtual reality education has also been shown to be a positive learning tool for online learning, especially when the COVID-19 pandemic was at its height. [6] Our research shows that the use of educational software in this field is somewhat limited, in terms of production readiness or the amount of content provided. The most available software is called "VFabLab", developed by a team at UC Berkeley [7]. This software is two-dimensional and can be played from a computer using a mouse and keyboard. This software is very useful for introductory labs since it helps familiarize players with the tools and techniques, but it is unable to simulate a proper workflow, since the user cannot use different equipment in sequence. This prevents the software from simulating a realistic nanofabrication recipe. Another example can be found at Utah Valley University [8-9]. A nanofabrication simulator was created with modules for photolithography, sputter deposition, etching, and characterization. However, each module is seen as a different level. While these levels do compose the fabrication process, it is not one seamless experience/fabrication flow. Another team at the University of Missouri have also created a nanofabrication simulator, with their gameplay covering only the sample preparation step.[10] A team at Norfolk State University developed an Augmented Reality software that created overlays onto the real-world machines within their cleanroom facility.[11] Their AR software currently did not have a "training" aspect to it yet, but exemplifies the exciting possibilities of how these ever-expanding extended reality technologies can be applied within the nanofabrication industry. It should be noted that virtual and augmented reality solutions are used extensively in other industries. An example is the use of augmented reality in surgery [12] with new developments in Head's Up Displays progressing rapidly. These would allow the surgeon(s) to stay focused on the procedure without having to look at multiple screens to interpret digital images, patient data and progress. Similarly, oil and gas industries are increasingly adopting virtual and augmented reality in their training and operations to increase the safety of their employees and prevent damage to expensive equipment. [13].

In this paper we introduce preliminary results on the design and educational evaluation of an immersive virtual reality cleanroom simulator that allows students to experiment safely with device nanofabrication flows. Section II covers the methods used in our work, including details on the simulation design versus our cleanroom facility, the software and hardware used, the exemplified process flow, as well as the educational mixed methods used to evaluate the user experience. Section III presents the simulation implementation results for a tutorial and one level of game play, plus the results of the student survey and interview. Section IV is a discussion highlighting the limitations and opportunities in improving the simulator and testing it as scale. We wrap up with conclusions in Section V.

2. Methods

2.1. Simulator design

The simulator is designed using inspiration from the layout and tools in the GWNIC. The simulator was created using the Unity game engine (Unity 2020.1.17f1). The floorplan of the simulator was created from scratch using Unity ProBuilder to mimic a similar layout to GWU's facility. Next, the key tools, machines, and furniture were created using the Blender modeling software.

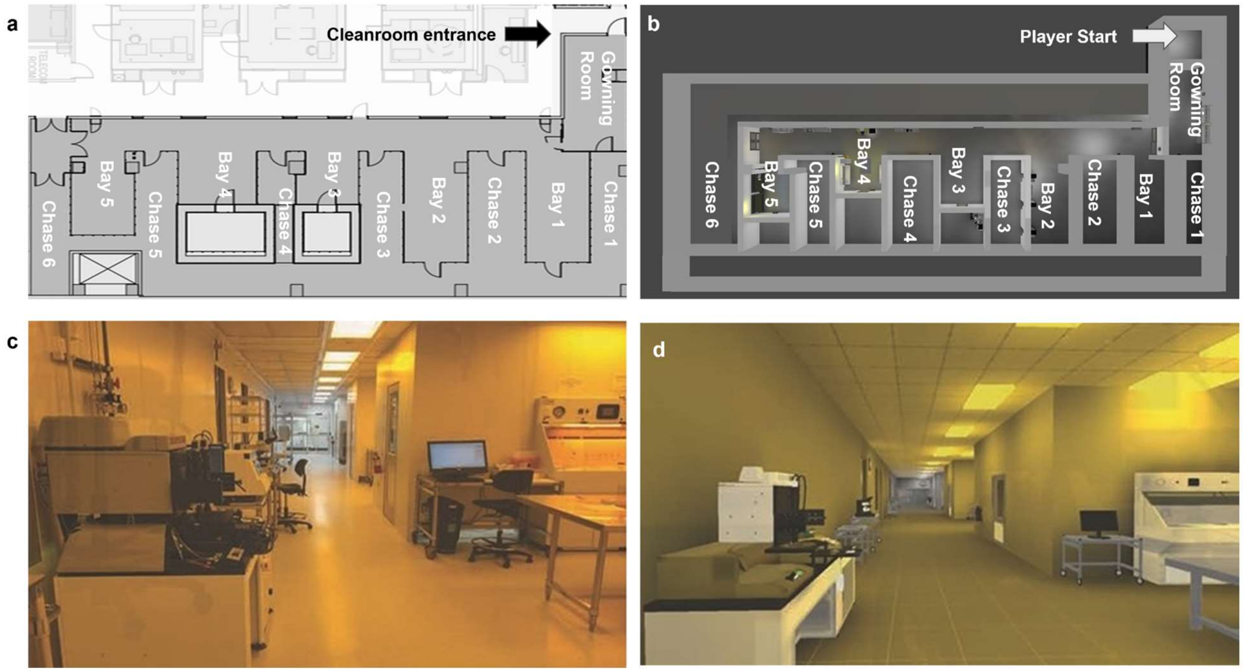

Fig. 1. Cleanroom facility vs. virtual reality layout. (a) Map of cleanroom layout; (b) Top down view of Unity model; (c) Picture taken in Bay 4 facing the gowning room; (d) Screenshot of simulator facing the same direction.

The nanofabrication processes that are covered in the gameplay are shown in Figure 2. As a model for the game, the cleanroom facility on campus and its instruments were used to fabricate and characterize a nano-scale resistor. To achieve this, the learner has to complete six steps: wafer cleaning/preparation, photolithography, metal deposition, metal liftoff, cleanup, and electrical characterization. From a user's perspective, this process flow exposes them to what each machine is and how it operates. Unlike available software, the user creates a device from start to finish and in the process they understand why each step is necessary.

The necessary tools, machines, and furniture were created using the Blender modeling software. Since many of the tools' CAD models and schematics are proprietary, the models were done by approximating the design and the measurements and are not exact replicas. It should also be noted that the simulator is played on the Oculus Quest (Figure 3), as camera and locomotion controls were provided by the Oculus software development kit. Currently, the simulator is played using the Quest linked to a laptop. A laptop is required to run it due to the size and graphical requirements of the simulator. While the Quest does have on-board processing capabilities, its rendering capabilities are highly limited, so the laptop offers more computational power. The laptop display seen in Figure 3 also allows the instructor to follow the learner's progress and see the learner is during the simulation.

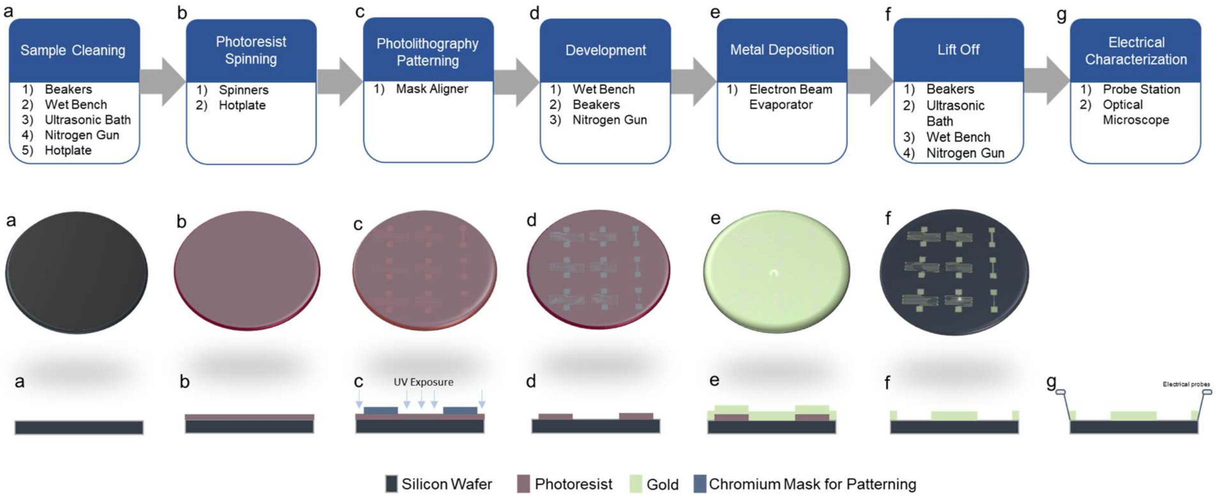

Fig. 2. Process steps and their order in the simulator. (a) Process steps (b) Top view of silicon wafer (c) Cross section of silicon wafer

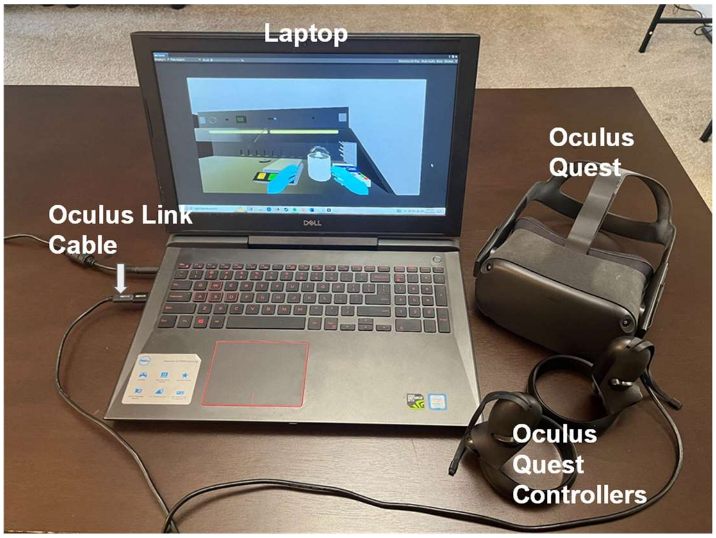

Fig. 3. Setup for playing the simulator. It includes an Oculus Quest Headset and a laptop to run the computing as well as serve as a secondary display.

2.2. Mixed methods study

We designed a mixed methods study to investigate how students in a nanoelectronics course utilized our virtual reality cleanroom prototype and what changes they recommended to improve its instructional value and usability. The study consisted of a quantitative → qualitative sequential mixed methods design [14]. Sequential mixed method design studies, which fall under the mixed method umbrella, consist of two methods that occur in different phases of a study, each applying different methods, and conducted sequentially. The quantitative phase supported the purposeful selection of participants in the qualitative phase. Quantitative methods consisted of a survey administered online using Qualtrics. The survey questions aimed to gather information about the user's prior experience with virtual reality and cleanroom environment, as well as statistics about the user's approach to the simulator itself, such as if the game was played sitting or standing, how many steps the user managed to complete before the allotted time, and if the user felt nauseous or dizzy. The users also rated the visuals, controls and the instruction features of the simulator. Moreover, the survey included questions consisting of pairs of contrasting attributes inspired by the User Experience Questionnaire [15]. For the purpose of this preliminary work-in-progress, 6 scales each with 3 items are studied. This approach contains Attractiveness, classical usability (pragmatic) aspects (Efficiency, Perspicuity, Dependability) and user experience (hedonic quality) aspects (Novelty, Stimulation/Fun of Use). Attractiveness measures users' overall impression of the product. Dependability looks at how much in control of the interaction a user feels. Efficiency assesses how fast the simulator reacts and how users can solve their tasks without unnecessary effort. Novelty measures the degree of creativity and originality of the virtual reality design. Perspicuity shows the ease of familiarizing with the game and learning how to use it, while Simulation gauges how exciting and motivating the game is.

Qualitative data collection involved an individual 25-minute interview with one participant for deeper insight about the learner experience. As this is a mixed methods study with an inductive research design, no specific scientific hypotheses were developed. This interview aimed first to gain a general understanding of the user experience overall, in particular what were their first impressions, and how they thought this simulator helped them in their understanding of nanofabrication. Secondly, we wanted to understand which features the participants liked or disliked, whether or not the instructions were accessible and if the navigation around the facility was easy. The answers to these questions will help shape future iterations of the game level and the simulator organization.

3. Results

3.1. Simulator implementation

The simulator was created to include a short tutorial and one level of gameplay. The nanofabrication tools were modeled using inspiration from their respective counterparts in the GWNIC. The list of models and their respective real-life tool includes: spin coater (Laurel Technologies), hotplates (Torrey Pines model), mask aligner (Neutronix NXQ4000), optical microscope (Olympus SC50), electron beam evaporator (CHA Criterion), sputter deposition machine (CHA Criterion), and probe station (Micromanipulator). The representative tools are shown in Figure 4. Other items necessary for the facility and processing flow were modeled such as access doors, shelves, tables, safety showers, personal protective equipment (PPE), wetbenches, air guns, beakers/glassware, tweezers, wafers, etc.

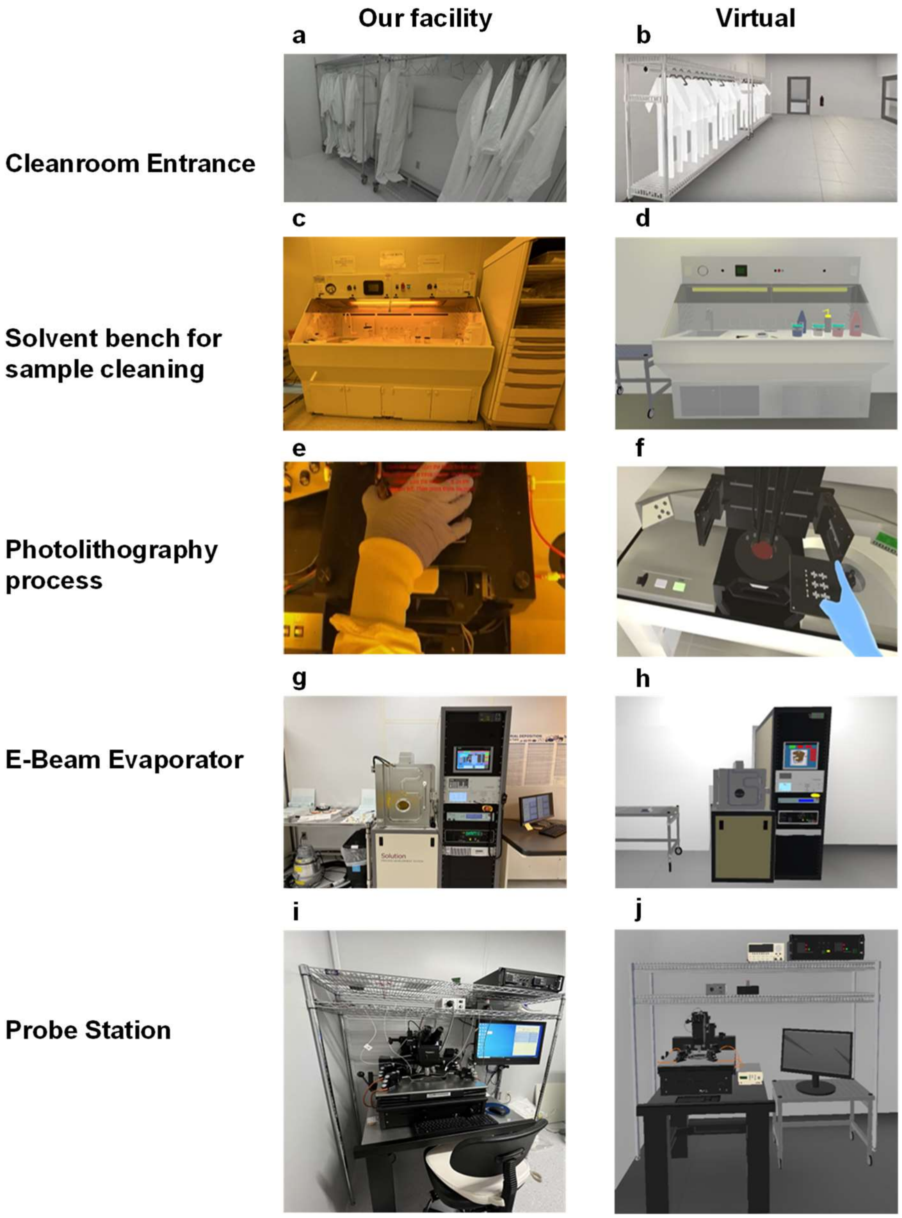

Fig. 4. Comparison of cleanroom facility to Simulator. (a) Gowning rack in facility; (b) Simulator model of gowning rack; (c) Wetbench in Bay 4 of cleanroom; (d) Same Bay 4 wetbench found in simulator; (e) User placing mask onto stage of mask aligner; (f) Simulator user placing mask onto stage of mask aligner; (g) E-beam evaporator in cleanroom; (h) E-beam evaporator in simulator; (i) Probe station in cleanroom; (j) Probe station in simulator

These tools were incorporated in the game as part of a process flow. This was enabled by several features as seen in Figure 5. Arrows are used heavily throughout the simulator, as navigating through a new environment is difficult for all new players in a game. A permanent arrow is placed above the user's left hand, and is controlled by the instruction controller script (Figure 5a) This arrow updates with each frame, showing the learner where the current task needs to take place. Other arrows are placed throughout the simulator as well. When a new area or tool is used, large red arrows point towards the tool. These arrows have local colliders that act as triggers to know when the learner has approached the tool or workstation. These arrows are also controlled by the instruction controller script, so they only show when certain steps have been reached.

Figures 5a, 5b, 5e, and 5f show the player's hands interacting with multiple objects within the simulator. These hand models are fully animated, so that the finger movements mimic the learner's interactions with their controllers. The models and their animations were provided by the Oculus software development kit. The hands' color was changed to the light blue color seen in Figure 5 to replicate the latex gloves that are worn in the cleanroom. These hand models are only able to pick up and interact with the necessary objects within the game to complete the process flow. The fingertips of both index fingers also contain code that we developed that allows them to interact with the many buttons on the different machines in the simulator.

The instruction system is the main guide for the learner during the fabrication process (Figure 5c). Instructions are given on the walls above each station or tool, or on a personal menu which the learner can see by holding either the Y or B button, Y for left handed players and B for right handed players. These instructions update as each task is completed, with certain events being the main "triggers". There is a central instruction controller script that keeps track of the learner's progress and what state each instruction is. There are multiple instruction locations throughout the process, placed in areas that should not take away from the task at hand. For the first step focused on sample preparation, instructions spawn above the wetbench that the learner is working at. For the second step, optical lithography, instructions appear above the tool as the learner uses the mask aligner. When they finish with development, the respective instructions spawn above the development wetbench. These instructions range in complexity, from as simple as "Press the Expose button" to full explanations regarding the tool functionality. The instructions along with walls are also given in a bright red text, so that they are easily seen and contrast with the facility's walls.

Multiple tools and doors within the simulator have been animated using Unity's built-in animation system. The different positions for each tool were keyframed, and then Unity handled the interpolation between points. The wafer is also animated during spin coating, with the photoresists slowly expanding to cover the entire surface of the wafer once the process is complete. The mask aligner is animated, shown in Figures 5d-e, with the front panel lifting to expose the wafer to ultraviolet light. The probe station and the microscope both have lens animations, so that the learner can change how zoomed in their image is. The probes on the probe station are fully controllable, so as the player turns different knobs for the x, y, and z axis respectively, they can see on the in-game monitor the probes moving in the axis being controlled. These animations, along with the many others in the simulator, not only depict the actual movements and controls of the machines, but also help increase the immersiveness of the overall experience.

The multiple tools that were modeled for this simulator include a long list of interactable buttons. As mentioned earlier, specialized code was created for the index fingers' fingertips to allow the learner to interact with these buttons in a realistic way. It was important to include every button on every machine, to further help familiarize the user with their location on the machine and its operation. All buttons are tied to the in-game audio system, and create a "click" sound every time they are pushed by the player's index finger. Since not all buttons change color, audio cues were extremely important to help indicate when they are pressed. Examples of the numerous in-game buttons are shown in Figures 5e-f, with the mask aligner and the e-beam evaporator.

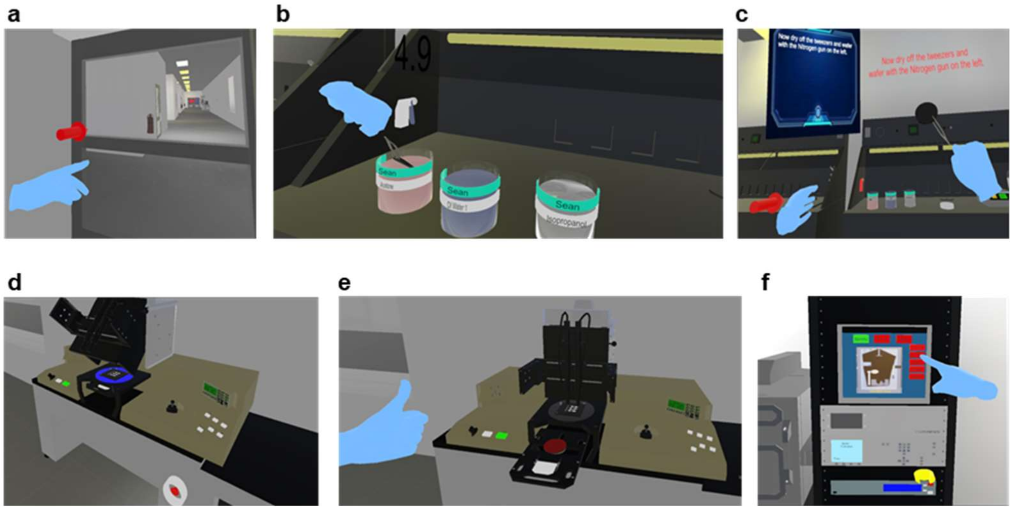

Fig. 5: Gameplay features (a) Guiding arrow above user's left hand; (b) User's hand holding a tweezer and dipping a wafer into acetone; (c) Example of instruction panel and on the wall; (d) Example of tool animation for exposing wafer to ultraviolet light; (e) User capable of operating virtual buttons for the mask aligner (f) Example of control panel embedded with animation to resemble the one on the real electron beam evaporation tool.

The tutorial level was implemented to get the learner familiarized with general movement and navigation in virtual reality, along with other controls for the simulator. Movement is extremely important to cover, as locomotion in virtual reality can oftentimes be disorienting to those who have not been exposed to virtual reality before. This level takes place in a small 8x8 room, with beakers to grab and instructions to follow. This level also familiarizes the learner with how tasks are sequentially presented to them through the instruction system. The user learns that the instructions can be found either on the walls above their workstation, or on a personal menu that can be opened and closed above either hand. The tutorial is self-paced without any embedded timer and it can take 1 - 5 minutes on average depending on the user's comfort with video games and virtual reality.

After the tutorial level is completed, the main simulation begins. This simulation can be played in training mode where the instructions are given or in game mode on a system of points without instructions. In the first game level, the learner starts in training mode at the entrance of the facility. The user is given a series of tasks, with the end goal being the fabrication of microscale resistors of different dimensions. The game is self-paced, with no timer forcing the learner to finish under a pre-set time. This feature was implemented to allow for a personalized experience, where each student can move at their own pace and focus on experimentation and learning rather than beating a clock. The user can also take off the headset at any point during the experiment, which will stop any player movement in the game, but allows the rest of the game to continue running. The experiment is completed once the electrical characterization is complete, and the player is moved to an ending screen notifying them that the experiment is complete and they can safely remove their headset. A second level was created to keep score, as the learner practices the same fabrication process in a competitive fashion. In this second level, the instructions are removed, and the learner can earn up to 100 points for completing tasks in the correct order. If they make a mistake, points are deducted. For the purposes of our survey, only the first level was used, since this was the participants' first time playing the simulator.

Fig. 6: Students playing the simulator (a) Students beginning the tutorial level; (b) Students performing sample cleaning in VR; (c) Student learning about chemical handling.

3.2. User satisfaction

3.2.1. Insights from the quantitative survey

While the sample size of the survey was small, the initial results from the survey provide insights into the areas that the simulator was successful and where there is room for future improvements. Four students had minimal experience with virtual reality, and one had zero experience, but all responders had some experience in the cleanroom from the nanoelectronics lab. In terms of learning objectives, the participants were asked: "*How much did the provided simulation help you understand what the layout of a cleanroom is?*". Three of the students answered "*somewhat*", while the other two answered "*significantly*". Understanding the layout of the cleanroom is important for the process flow itself, knowing where all the tools/machines are, but it is also a major component of cleanroom safety training, understanding where the exits are, where shower and eyewash stations are, or where chemicals are stored and used. Another question asked was, "*If you were tasked to use the mask aligner or e-beam evaporator by yourself, would you know what to do?*" All students answered that they have a rough idea of how to operate them, but need more training. This kind of answer was expected, as these tools are extremely complex and have a long series of sequential steps shown in the simulator. Regardless, giving students a head start in their learning about these tools is beneficial for both themselves and the cleanroom staff who administer the training. Having new cleanroom users who are already familiar with the device makes training easier for individuals. More work can be done to make the machines more accurate in the simulator, but having students walk away with some understanding is a major success when the devices are this complex.

Our survey also aimed to understand how participants played the simulator and rated the major components of the simulator, namely the visuals, controls, and instructions. 80% of the learners utilized the simulator alternating between sitting and standing positions, while the remaining 20% preferred a standing position. This observation is important to consider when planning for utilizing the simulator in the classroom with a larger number of students. More space is needed to play in a standing position and the environment needs to be free of furniture to not cause any accidents while the learners are immersed in the simulator. The learners rated all the simulator features as satisfactory or better which contribute to the immersiveness of the experience (Fig. 7). No aspect of the simulator was rated as poor which is encouraging, although issues related to the instructions and controls need to be improved. For instance, the students recommended that the visuals of the models look more realistic.

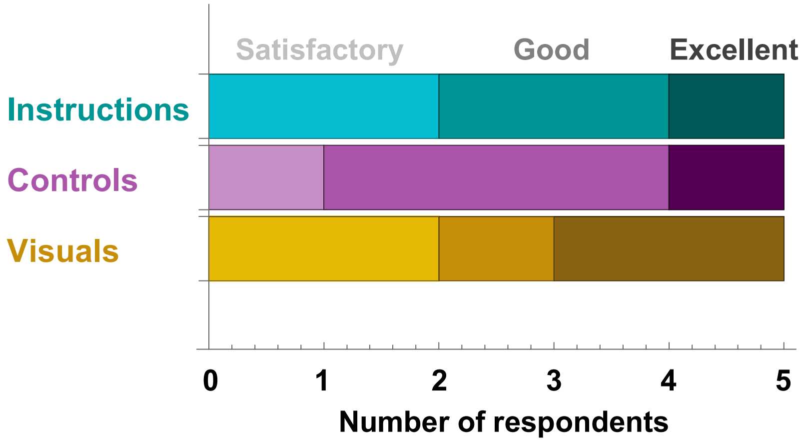

Fig. 7: Ratings provided by participants for the different features of the simulator

Nevertheless, one of the biggest issues reported in the survey was for the question, "*How did you feel while wearing the headset?*" This question allowed the participants to fill in multiple answers, with the choices being "*perfectly fine*", "*dizzy*", "*nauseous*", or "*other*". None of the participants answered "perfectly fine." The majority answered "dizzy," and two students answered "nauseous." This concerning side-effect might be due to the type of locomotion or movement controls that are used in the simulator and is amplified by the lack of prior experience of the learners with virtual reality environments.

Fig. 8 analyzes the data consisting of pairs of contrasting attributes for pragmatic aspects and hedonistic aspects inspired by the User Experience Questionnaire. In terms of the pragmatic aspects, dependability seems to be a more major concern, particularly the predictability ranging quite low. The users had mixed ratings to the simulator meeting the expectations in its current

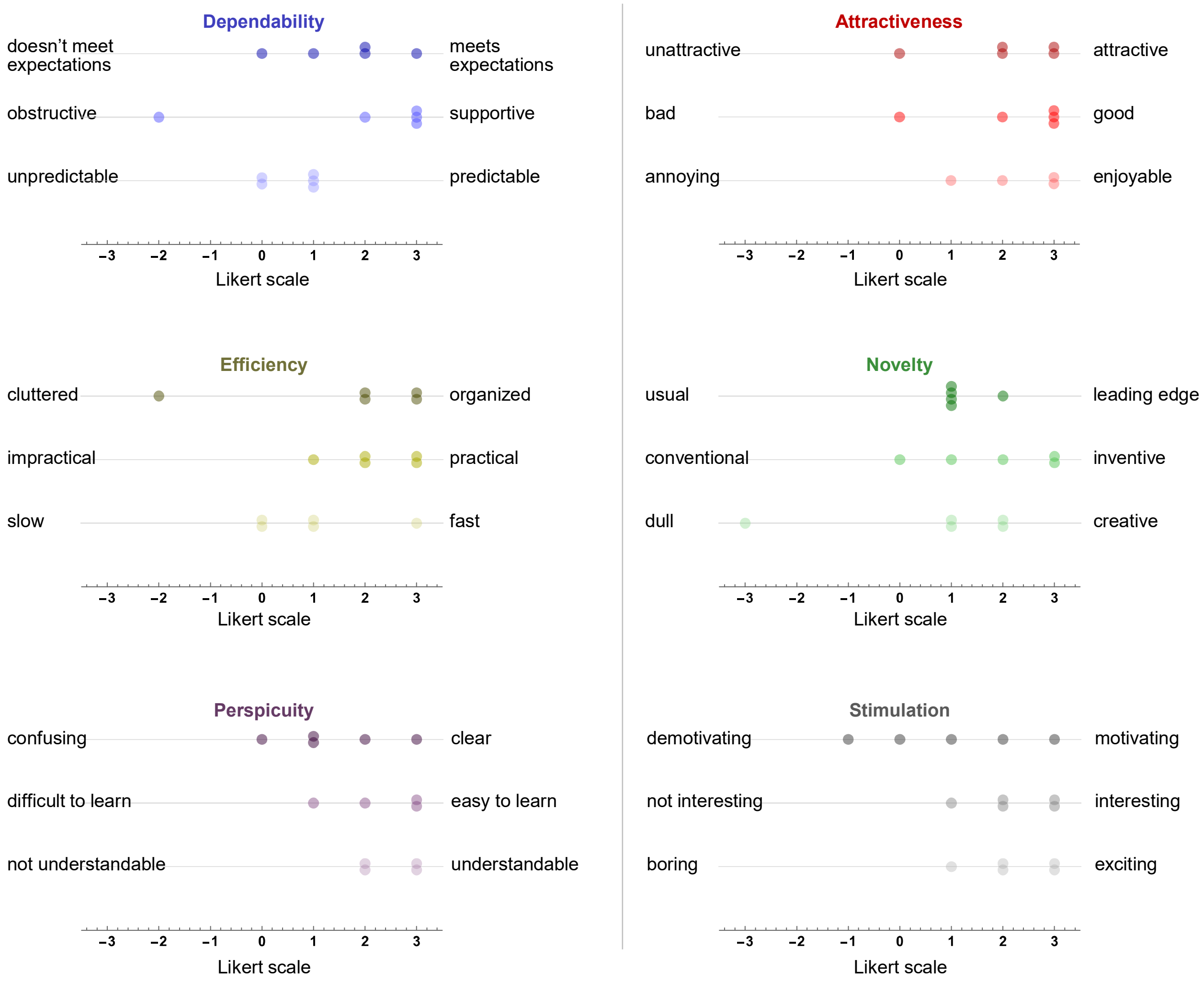

Fig. 8: Likert ranking of pragmatic aspects (Dependability, Efficiency, Perspicuity) and hedonistic aspects (Attractiveness, Novelty, Stimulation).

form, hinting at the need for future improvements. A major current concern is likely due to the issues with computing power and capability for real-time use without bugs as emphasized by the efficiency metric that reported the speed. On the other hand, the learners seem to appreciate the practicality and the organization of the simulator. The learners also rated the perspicuity high, particularly the understandability and ease of learning scoring on the higher end of the Likert scale. One concern is that some students found it somewhat confusing which might hint at a need to improve the instructions.

In terms of the hedonistic aspects, the majority of the learners rated the simulator as enjoyable, good and attractive. The novelty also ranked high. An interesting observation is that a user found it dull (scale -3), although rated it as highly inventive (scale 3) and very creative (scale 2) at the same time. This might be due to the issues related to the currently practical implementation which frustrated the learner, as highlighted by the predictability metric (which this learner rated as 0). The implementation issues also seem to have demotivated some of the users and reduced the stimulation and immersiveness of the experience. Nevertheless, the learners rated this experience as interesting and exciting.

3.2.2. Insights from the qualitative interview

The Zoom interview highlighted several positive features and some recommendations for improving the simulator. The learner found that the game represented well the overall process of the nanofabrication. They described it as a very interactive tool that is easy to use depending on the level of prior experience in the cleanroom. It is more engaging than computer-based lab experiences they have had in some of their classes.

The learner highlighted the need for a manual or short video to familiarize them with the virtual reality game and the steps of the fabrication process presented before the start. It appeared that the tutorial level at the beginning went over the controls well enough, but not the overall process flow. They found the arrows and the instructions useful, however they would have preferred to see a checklist of what they have to do to complete the level and where they are in the overall process.

The fact that the simulator allowed the learner to make mistakes and restart the experience at their own convenience was considered very useful. However, the need to start from the very beginning, i.e., entering the hallway of the lab, was considered a waste of time and effort. They would prefer the option of restarting the simulator at a previously saved process step. Overall, the semi-structured learner interview was in line with the quantitative results and provided triangulated insights. It reiterated that the concept of the proposed simulator is exciting, innovative and practical, but needs more refinement in order to become user-friendly and function as a stand-alone learning tool.

4. Discussion

The results provide recommendations for improvement and next steps for developing the simulator further. Some improvements are relatively easy to implement and will be prioritized in future iterations. The first one is related to user interface improvements, for example the visual style and placement of the instructions. User interface design is often a field within itself, and much research has already been done discussing the most optimal designs from the user perspective.[16] While the red text is vibrant and easy to read, it does not seem to fit in with the overall cleanroom environment and experience. There are many possible user interface improvements that can be made to the simulator, namely making all UI "fit in" with the cleanroom environment. For example, in the GWNIC, learners are encouraged to make note of the needed machine operation steps and recipes inside a personal notebook. This idea could also be implemented in the simulator, with steps being written in a virtual notebook in a menu that the user can show whenever needed. This would also acclimate them to the idea of carrying around their notebook within the cleanroom and the importance of documentation. While optimizing the user interface was not the primary focus of this preliminary version of the simulator, it is clear from the learners' feedback that improving its effectiveness, including possibly the development of a leaderboard, is needed to achieve an engaging user experience that supports the learning objectives. The learners also pointed out minor bugs that made the simulation experience unpredictable and demotivating. Work is under way to address them.

Moreover, the user experience with the controls also needs improvement. For example, the users were having a difficult time using the virtual tweezers and moving in the space simultaneously, as the tweezers would require them to take their hand off the movement joystick. The participants were shown that by holding the tweezers in the other hand, they could move and hold the tweezers simultaneously. Nevertheless, this control scheme did seem to confuse many of them and a user found it challenging and obstructive. This control feature will be improved by devising a better control scheme. We plan to run tests with different control schemes and navigation methods to see what the learners prefer. We will also incorporate more practice using this optimized control scheme as part of the tutorial.

Another important recommendation for improvement that is a priority for future versions is a saving system. A saving system would allow learners to start at different points of the process flow if they had completed other steps. It would also ensure that the learners have their progress saved in case the simulator crashes. A saving system would also allow the game to be broken up, decreasing any possible cognitive overload and letting the learner take off the headset after each step, to relieve any nauseating sensations they could experience while in virtual reality.

While allowing learners to take breaks during the simulation can provide more comfort during the experience, it is important to optimize the virtual reality cleanroom environment to avoid nausea and dizziness as much as possible. Until virtual reality becomes more prominent for consumers, it is clear that walking for locomotion can not be used since it is too disorienting for new users. The learning effectiveness of the simulator cannot be properly measured if the learners are not physically comfortable. One method to reduce the nauseating effects of virtual reality would be to implement a teleporting form of locomotion, allowing the player to point their controller towards a location, press a button, and spawn at that new location. This type of locomotion has been shown to reduce the feelings of nausea or dizziness while using virtual reality tools [17]. Another possible improvement could be implementing what is known as a “tunneling” effect to the learner’s field of view as they move. This effect shrinks the learner's field of view slightly as they move, which has also been shown to decrease the nauseating effects virtual reality can have on first time users.[18] The best system would be a user preference menu system, that would allow learners to select their preferred method of locomotion.

Improved versions of the simulator will be tested in the future with a larger number of learners from diverse backgrounds to ensure that these issues have been addressed with feedback from a variety of perspectives. Once the design parameters of the simulator have been optimized, additional educational levels with more complex process flows will be added. Future work would require additional tools to be modeled, animated, and incorporated. A priority for us is modeling a process flow for photonic devices that require the use of electron beam lithography and inductively coupled plasma etching [19]. Another potential level would focus on the fabrication flow of emerging devices that require multiple iterations of lithography and thus careful alignment, for example memristor devices organized in matrices [20]. Such realistic process flows implemented in simulation would bridge the gap between classroom education and hands-on experimentation, thus potentially raising the interest of more students in related applied research. Addition of a leaderboard could also improve user ability to track progress.

5. Limitations

This preliminary study has been conducted with a work-in-progress simulator and with a limited number of participants. These limitations affect its internal and external validity. Given the very small sample size, the data was not statistically analyzed. Also, because of its limited scope at this time, the results of this preliminary exploration cannot be considered generalizable. Nevertheless, this study is a key step towards the development of a realistic and reliable virtual reality cleanroom simulator. Future work will iteratively address the limitations and refine the simulator and its testing from a user experience perspective as part of the design thinking process.

6. Conclusions

The goal of this work was to develop a virtual reality cleanroom inspired from a real academic cleanroom facility and test its usability for education. The learners benefited from an immersive experience in virtual reality with an accessible nanofabrication process that introduces students to multiple tools and processes that take place during a fabrication process. Undergraduate and graduate students in a nanoelectronics-related class at a major research university tested the simulator and participated in research about their experience. Although the number of participants was limited, the preliminary results show that virtual reality can be an impactful tool for learning and workforce development in this resource constrained field. Nevertheless, this study is a work-in-progress and future iterations will be needed to improve the overall experience. Moreover, such a virtual reality cleanroom simulator will likely become an important educational tool in nanofabrication. Using the proposed simulator, students in large or online classes and K-12 students and teachers in outreach events would have the opportunity to conduct realistic process workflows, as well as to learn how to use the nanofabrication cleanroom lab through safe trial and error in virtual reality experiences.

Acknowledgements

The authors would like to thank the IEEE Electron Devices Society (grant 2022.15) and the National Science Foundation (grant CAREER #2239951) for their generous support. We would also like to acknowledge support from the George Washington Summer Undergraduate Program for Engineering Research award and a GW Undergraduate Research Award. We would also like to thank the George Washington Nanofabrication and Imaging Center team for their guidance.

Data Availability Statement

The simulator that supports the findings of this study can be made available by the corresponding author upon reasonable request.

References

[1] M. T. Postek, and R. J. Hocken (Chairs), “Instrumentation and Metrology for Nanotechnology”, Report of the 2004 National Nanotechnology Initiative Workshop, Arlington, VA: National Nanotechnology Coordination Office, 2006. Available online: https://www.nano.gov/sites/default/files/pub_resource/nni_instrumentation_metrology_rpt.pdf

[2] Zion Market Research. “Nanofabrication Market - by Application (Medicine, Pharmaceutical, Molecular Biotechnology, and Cell Biology) and by Region, Global Industry Analysis, Size, Share, Growth, Trends, And Forecast, 2020-2026”. Available online: https://www.zionmarketresearch.com/report/nanofabrication-market

[3] S. Kavanagh, A. Luxton-Reily, B. Wuensche, and B. Plimmer, “A Systematic Review of Virtual Reality in Education,” in *Themes in Science & Technology Education*, vol. 10(2), pp. 85–119, Dec. 2017.

[4] L. Freina and M. Ott, “A Literature Review on Immersive Virtual Reality in Education: State of the Art and Perspectives”, in *The International Scientific Conference e-Learning and Software for Education*, vol. 1, pp. 10–1007, Bucharest, Romania, Apr. 2015.

[5] H. S. F. John and T. Bell, ‘Ten Steps to Developing Virtual Reality Applications for Engineering Education’, in *Proceedings of ASEE Annual Conference*, Milwaukee, WI, USA, Jun. 1997.

[6] M. J. K. Chadia and A. Aji, ‘Virtual Reality in STEM Education During COVID-19’, in *Proceedings of ASEE Annual Conference*, Virtual, Jul. 2021.

[7] vFabLab. Available online: https://vfablab.org

[8] R. Kamali-Sarvestani, P. Weber, M. Clayton, M. Meyers and S. Slade, "Virtual Reality to Improve Nanotechnology Education: Development Methods and Example Applications," in *IEEE Nanotechnology Magazine*, vol. 14, no. 4, pp. 29-38, Aug. 2020.

[9] Reza Kamali Jonathan David Anderson and M. Meyers, ‘Comparison of Virtual Reality Versus Reality: Effects on Student Learning Using Virtual Technology on Nanotechnology Education’, in *Proceedings of ASEE Annual Conference*, Tampa, FL, USA, Jun. 2019.

[10] F. Wang, X. Xu, W. Feng, J. A. Bueno-Vesga, Z. Liang and S. Murrell, "Towards an Immersive Guided Virtual Reality Microfabrication Laboratory Training System," *IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, Atlanta, GA, USA, pp. 796-797, Mar. 2020.

[11] M. Kozhevnikov, “Virtual Reality to Improve Nanotechnology Education,” *MODSIM World*, no. 25, 2022. Available: https://www.modsimworld.org/papers/2022/MODSIM_2022_paper_25.pdf

[12] W. S. Khor, B. Baker, K. Amin, A. Chan, K. Patel, and J. Wong, ‘Augmented and Virtual Reality in Surgery—The Digital Surgical Environment: Applications, Limitations and Legal Pitfalls’, *Annals of Translational Medicine*, vol. 4, no. 23, Dec. 2016.

[13] R. Goswami. “AR and VR can Solve Many of Core Oil and Gas Challenges” Available: https://www.infosys.com/insights/industry-stories/ar-vr-in-oil-gas.html

[14] J.M. Morse, “Principles of Mixed Methods and Multi-method Research Design,” in *Handbook of Mixed Methods in Social and Behavioral Research,* C.Teddlie, A. Tashakkori, Eds., Thousand Oaks, CA: Sage Publication, pp. 189-208, 2003.

[15] B. Laugwitz, T. Held, M. Schrepp, “Construction and Evaluation of a User Experience Questionnaire,” in USAB 2008: *Proceedings HCI and Usability and Education for Work, in* Lecture Notes Computer Science, vol. 5298, A. Holzinger, Ed. pp. 63-76, Nov. 2008.

[16] D. A. Bowman, E. Kruijff, J. J. LaViola and I. Poupyrev, "An Introduction to 3-D User Interface Design," *Presence*, vol. 10, no. 1, pp. 96-108, Feb. 2001.

[17] M. McCaffrey, “Chapter 9. VR Locomotion,” in *Unreal Engine VR Cookbook: Developing Virtual Reality with UE4*, Addison-Wesley, Feb. 2017.

[18] S. Vlahović, M. Suznjevic and L. S. -. Kapov, "Subjective Assessment of Different Locomotion Techniques in Virtual Reality Environments," in *Proceedings of the 10th International Conference on Quality of Multimedia Experience (QoMEX)*, Cagliari, Italy, May, 2018.

[19] Y. Su, Y. Zhang, C. Qiu, X. Guo, and L. Sun, ‘Silicon Photonic Platform for Passive Waveguide Devices: Materials, Fabrication, and Applications’, *Advanced Materials Technologies*, vol. 5, no. 8, p. 1901153, Jun. 2020.

[20] G. C. Adam, B. D. Hoskins, M. Prezioso, F. M. Bayat, B. Chakrabarti and D. B. Strukov, "Highly-uniform multi-layer ReRAM crossbar circuits," in *Proceedings of the 46th European Solid-State Device Research Conference (ESSDERC)*, Lausanne, Switzerland, pp. 436-439, Sept. 2016.