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Virtual Reality Implementation of a Scanning Electron Microscope in Nanotechnology Education

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Abstract

A virtual reality representation of a scanning electron microscope was developed to be used as a pedagogical tool to train students in its proper use. This will enable students to have full access to a scanning electron microscope in the classroom and learn the processes of creating a sample, which will help solidify the abstract concepts presented to them throughout their education in nanotechnology.

A training session to learn the basic procedure for using the scanning electron microscope was developed. These procedures were practiced and then presented to a team of programmers who created a virtual reality version of the microscope. Several processes were documented to create this pedagogical tool for the classroom: An understanding of the correct procedures and protocol when using the scanning electron microscope, how the microscope images a sample, the processes to view samples, creating biological and non-biological samples, the process of sputter coating nonconductive samples, and what is involved in the sputter coating process.

These processes, along with a representation of the machine were created in virtual reality to give students a tool to help see and understand abstract concepts presented to them during their education in nanotechnology. Students entering the virtual reality laboratory use hand motions via virtual reality controllers to manipulate the virtual reality lab and perform a complete scanning electron microscopy experiment. As they interact with the virtual reality lab, messages and warnings guide them through the safe manipulation of the virtual scanning electron microscope. They are then prepared to use a real SEM in the lab or in the workforce. By working with the team creating the virtual reality representation of these processes a tool that instills real laboratory techniques before the students even encounter the physical instrument was created.

This Virtual Reality lab will benefit institutions who do not have access to a scanning electron microscope and better prepare students in advance to work safely and effectively with the scanning electron microscope. Unfamiliarity with scanning electron microscope function can result in mistakes causing damage to the sample stage, detectors, and microscope column. Such damages can require thousands of dollars to repair. Students trained via the virtual scanning electron microscope laboratory learn correct safety procedures in the virtual lab, often through trial and error, and are far less likely to repeat those errors in future use of a real scanning electron microscope.

1.0 Introduction

Nanotechnology is the science, engineering, and technology that deals with various structures of matter that have dimensions on the order of a billionth of a meter. Nanotechnology is the ability to observe, manipulate, measure, and manufacture things at the nanoscale, which is about 1 to 100 nanometers. While the word nanotechnology is new and was introduced in the late 1970s, the existence of functional devices and structures of nanometer dimensions is not new, and actually such structures have existed on earth as long as life itself [1].

The idea behind nanoscience and nanotechnology started with Richard Feynman's (Father of nanotechnology) visionary talk "There is plenty of room at the bottom" at the 1959 meeting of the American Physical Society at the California Institute of Technology [2].

The National Nanotechnology Initiative (NNI) calls something nanotechnology only if it involves all of the following [3]:

- "Research and technology development at the atomic, molecular, or macro-molecular levels, in the length scale of approximately 1 to 100-nanometer range.
- Creating and using structures, devices, and systems that have novel properties and functions because of their small and/or intermediate size.
- Ability to control or manipulate on the atomic scale."

"The vision of the NNI is a future in which the ability to understand and control matter at the nanoscale leads to a revolution in technology and industry that benefits society." [4] The following are four goals of the NNI in order to achieve its vision:

1. "Advance a world-class nanotechnology research and development program.
2. Foster the transfer of new technologies into products for commercial and public benefit.
3. Develop and sustain educational resources, a skilled workforce, and the supporting infrastructure and tools to advance nanotechnology.
4. Support responsible development of nanotechnology." [4]

Nanotechnology is a key technology for the 21st century. Nanotechnology can offer better built, longer lasting, cleaner, safer and smarter products for home, computing, communications, medicine, transportation, agriculture, aerospace, energy, and information technology [5].

Advances in nanotechnology are helping to considerably improve, even revolutionize, many technology and industry sectors: information technology, energy, environmental science, medicine, homeland security, food safety, and transportation, among many others [5].

Over the last few decades, nanotechnology has gained considerable attention in scientific research and industry. As previously stated, the NNI defines nanotechnology as "science, engineering, and technology conducted at the nanoscale, which is about 1 to 100 nanometers" [6]. Though this definition applies to a wide range of subjects including chemical and biological systems, a large focus of nanotechnology is the development of smaller integrated circuits and electrical components. Recent years have seen significant breakthroughs in the minimum feature size for transistors in particular, including an impressive discovery by Berkley labs in which they used carbon nanotubes and a chemical compound molybdenum disulphide to construct a transistor with a 1nm gate [7]. Such breakthroughs pave the way into developing more compact and capable computing technologies and are therefore essential to technology innovation and industry. These discoveries are made possible by instruments such as the scanning electron microscope (SEM) which enable scientists to visualize and manipulate matter on a nanometer scale.

Figure 1: Tescan's Vega 3 SEM [8].

The SEM has revolutionized the study and development of nanotechnology fabrication and measurement. Since its conception in 1931 by physicist Ernst Ruska and electrical engineer Max Knoll [9], the SEM has enabled imaging at a nanometer scale, granting access to a whole new world of modern innovation. Unlike conventional light microscopes, the SEM uses an electron beam to image samples. This circumvents the magnification limits of optical microscopes due to the diffraction factor of visible light [10]. Combined with its counterparts the atomic force microscope (AFM) and other similar imaging techniques, the SEM enables construction and visualization of microscopic integrated circuits and other technologies. The SEM is especially important because it can be used for electron-beam lithography, a lithography technique that utilizes the SEM's precise electron beam to fabricate electronic components only a few nanometers in scale. An SEM also has greater depth of field than some other methods (such as the AFM) [11] and can generally provide sample data more quickly than other high magnification devices [12]. These characteristics make the SEM irreplaceable in research and industrial applications.

Because the SEM is a fundamental tool in the nanotechnology industry, it is essential that students preparing to enter the work force become familiar with this device. During the development of the SEM training method described in this paper, the authors had the opportunity to step into the SEM laboratory to image a sample. We determined that it would be very difficult for a student, without prior knowledge and training of the SEM and its functions, to operate this device in the workforce. The high cost associated with purchase, maintenance, and use of the SEM, however, prevents many small colleges and universities from implementing SEM training. Most SEMs cost several hundred thousand dollars, with high end SEM's approaching $1 million [13]. Additionally, creating an adequate laboratory environment for SEM imaging can be even more expensive and can be difficult for institutions with space limitations.

One solution to the high cost and material demands of a real SEM laboratory is to implement the same experience using virtual reality (VR) technology. VR equipment can be purchased at a reasonably low cost, with most high-end systems sitting between $400-$600 [14,18]. The concept of using VR as a teaching tool is not new, in fact it has already been implemented in many educational topics such as chemistry, biology, and mathematics. Use of VR in the instruction of nanotechnology, however, has never been fully implemented and offers, as do other forms of VR education, a unique approach to effective student learning. Because the VR environment engages multiple sensory levels in the user, the VR platform can enable students to learn in the way most effective to them [15]. In addition to enhancing learning through increased sensory input, application of VR technology allows educators to visualize phenomenon in a way that would otherwise be impossible [16]. These benefits, combined with the relatively low cost of implementing a VR framework, make VR scanning electron microscopy an effective alternative to a real SEM laboratory.

With this in mind, a team of researchers and students (including the authors) at Utah Valley University (UVU) investigated VR as a strategy for familiarizing students with the SEM, a strategy we hope will be disseminated to additional colleges and universities to better prepare the next generation of nanotechnology engineers. Using VR hardware, the team designed a VR lab incorporating a SEM for use in training students and faculty. The complete VR lab includes four different rooms containing essential tools used in nanotechnology fabrication. The virtual SEM is located in a room designated for measurement which also includes a virtual light microscope. Other rooms include a photolithography room, an etching room, and a room for thin film deposition. This paper focuses on the SEM module of the VR project.

2.0 Rational

The goal of the SEM module is to enable students to become familiar with the features, capabilities, and controls of the SEM in a cost effective, safe, and interactive environment, prior to, or in the place of, using a real SEM. Benefits of using the VR SEM are listed below.

Cost effective

The VR SEM can negate costs associated with SEM education in the following ways:

- Reduces the high energy and material costs of running the SEM continually during student training.

- Enables multiple students to perform SEM procedures simultaneously without having to purchase numerous expensive microscopes.
- Provides institutions without resources to afford costly SEM equipment a way to give students SEM training by implementing the VR SEM experience.
- Reduces repair and maintenance costs caused by incorrect use of SEM.

Safe

The VR SEM provides the following safety advantages to students and equipment:

- Students gain experience controlling working distance and sample stage adjustments without running the risk of damaging SEM components.
- Reduces wear and tear on the SEM and sputter coater.
- Prevents contamination of SEM components due to improper handling.

Interactive

The VR SEM provides the following benefits through VR interaction:

- Students take primary responsibility for their own SEM experiments in the VR lab, increasing student comprehension and solidifying SEM procedural steps in students minds.
- The VR SEM enables students to peer inside SEM column and chamber during use to see scanning electron beam in action.
- The VR simulation provides damage feedback and visuals when safety guidelines are not followed to help students understand and remember safety procedures.

These combined benefits make the VR SEM module an effective and beneficial tool in enhancing SEM education. Such potential educational and financial advantages led to the development of the VR SEM module.

3.0 Module Implementation

The VR SEM module is broken up into four phases in order to most effectively equip students to use the SEM. The first phase of the module involved development of the nanotechnology team and construction of the VR lab and course material for the following phases. In the second phase of the module, students are taught the history of the SEM and its importance in modern nanotechnology measurement and fabrication. Here they gain a better understanding of size and scale to help them understand the scope of SEM magnification. They also learn the basic theory behind operating an SEM in order to prepare them to enter the VR lab. In phase three, students enter the VR lab and interact with the SEM simulator in order to learn SEM controls and procedures, and to help them internalize necessary safety precautions so they are ready and able to use a real SEM later on. They also use the VR SEM experience to familiarize themselves with the process of taking nanoscale measurements. In phase four, after students have proven they can use an SEM in the VR lab, students are granted access to a real SEM in order to test their knowledge of SEM functionality and to provide additional SEM experience. The goal of the nanotechnology team in designing the VR SEM was to mimic real-world use of the SEM in the VR lab to a degree that students trained only via the VR simulation are capable of using a real-world SEM without additional training. Further testing is needed to assess the effective replacement of a real SEM, but if the VR SEM teaching model proves successful, the fourth phase (use of a real SEM) could be omitted by institutions lacking adequate resources to construct an SEM lab. The four phases of this module are explained in detail in the following paragraphs.

3.1 Team Development

The first phase of the VR SEM module began with the construction and professional development of a nanotechnology team at UVU. A group of students was selected from computer science, engineering, and physics departments forming ten students in all. Students were selected and assigned various responsibilities based on their experience, field of study, and perceived ability to accomplish the tasks required. Team responsibilities included SEM familiarization and lab development, lecture material development, and construction of the SEM simulator using VR software. Team members were also selected for development of a VR nanotechnology website to increase dissemination of the project results and implementation. Students collaborated under the direction of UVU researchers with doctorates in computer science and engineering who provided direction and ensured accuracy of educational material and experiments.

Lab procedures and instructions were tested by various members of the team to ensure clarity and repeatability and to further unify the team's efforts. The VR SEM was tested by four members of the team responsible for lecture material and lab development to ensure correct lab procedures were integrated. Instructions for the real SEM lab experiment were also tested on three other team members to ensure procedure steps were clear and accurate. UVU researchers also analyzed the experiments to ensure accuracy of information and procedure steps. The resultant material generated by the nanotechnology team was then available to students at UVU in the next phase of the project.

3.2 SEM Education

In the second phase of the VR SEM module, students are educated in the functionality and application of the SEM. This is done through a series of lectures created by nanotechnology team members from UVU's engineering and computer science departments. Educational aids include PowerPoint slides and SEM diagrams to facilitate visualization of the microscopy process. Figure 2 shows one such diagram displaying the components of the SEM column in a CAD model of the device. Other visualization aids include sample images produced by an SEM that show the devices potential. Through the use of these and other materials, students are introduced to scanning electron microscopy. They are also given an introduction to E-beam lithography and other nanotechnology applications of the SEM.

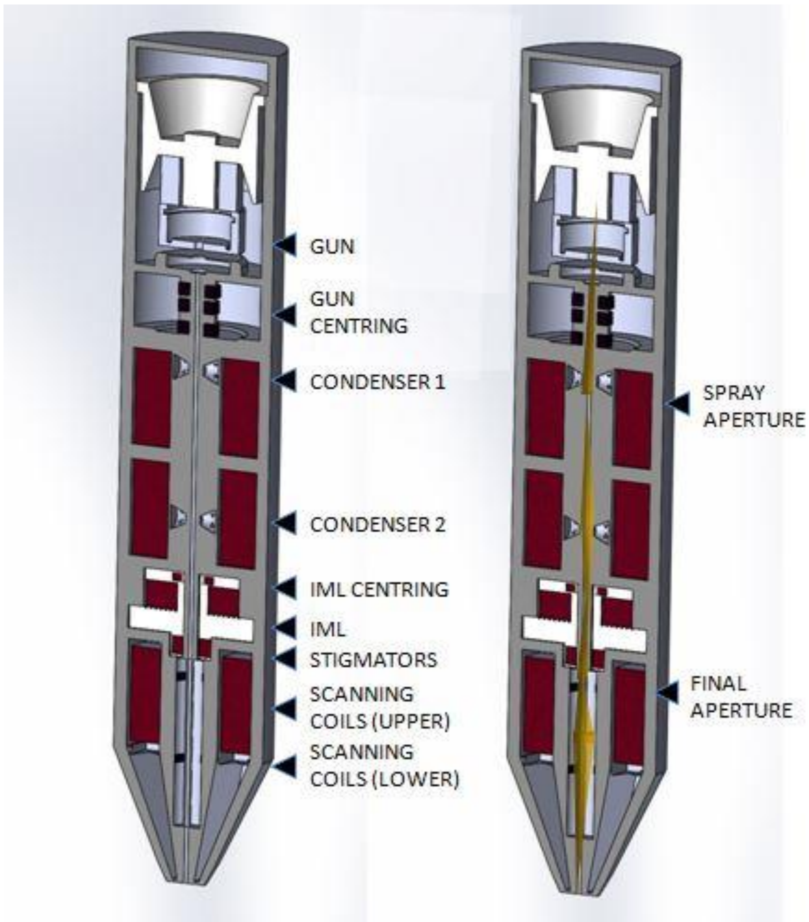

Figure 2: CAD Model of SEM Column Displaying Components Used in Manipulation of Electron Beam.

In addition to learning how an SEM functions, students are given detailed instruction involving operation of the device. This instruction begins with sample preparation in which students are taught SEM specifications for standard (non- biological) samples. Students are also educated in the purpose and implementation of a sputter coater. Students are then taught the safety practices required to use an SEM.

Instructors also teach students the basics of manipulation of beam intensity, working distance, magnification, brightness and contrast, and astigmatism correction in the development of a clear image. Finally, students are trained in the acquisition of SEM images and available measurement procedures to analyze them. Students are then permitted to enter the next phase of SEM education through use of the VR lab.

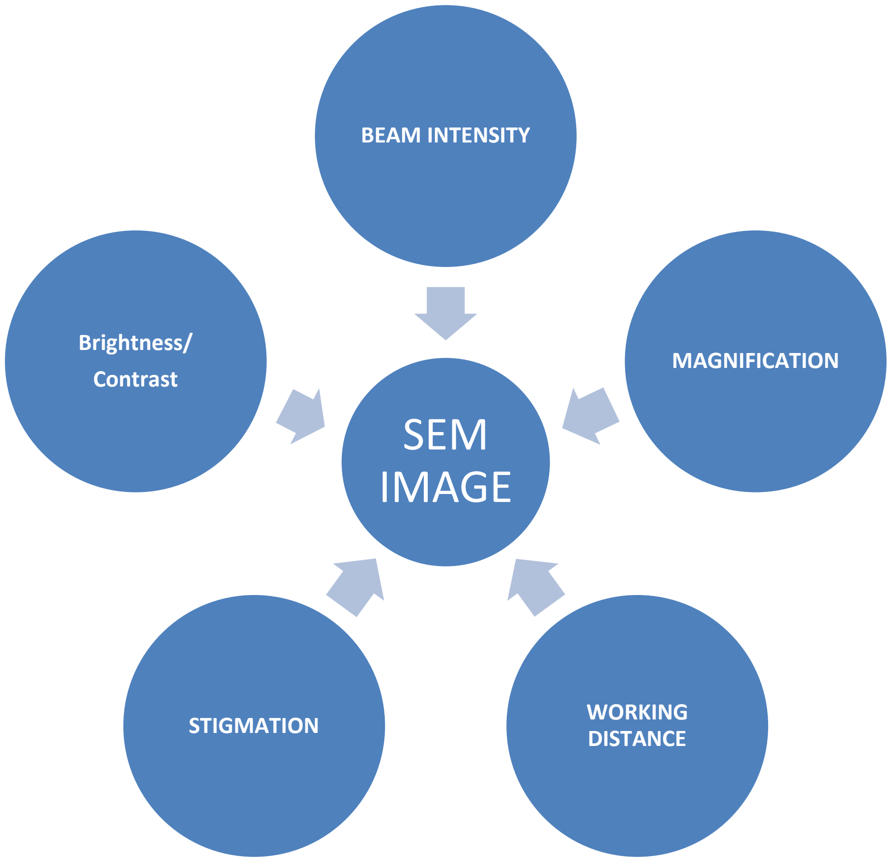

Figure 3: Components of SEM Image Adjustment.

3.3 VR SEM Laboratory

The third phase of the module introduces students to the VR SEM laboratory where they are able to perform experiments using the VR SEM simulator. In order to accomplish this, team members from UVU's Computer Science Department developed an SEM simulation using VR software Unity 3D, with a plug-in Virtual Reality Toolkit (VRTK) to enable VR capabilities. An additional graphics card was needed in order to run the software, and team members selected NVIDIA's GeForce GTX 1080 Ti [17] (see figure 4), a graphics card designed with VR in mind.

HTC Vive was selected as the hardware of choice due to its compatibility, room-scale stage size, and safety features [18]. The program incorporates all aspects of the SEM experience including sample preparation, microscope initialization, imaging and adjustments, and shutting down the microscope after use.

Figure 4: GeForce GTX 1080 TI Graphics Card [17].

To begin the VR SEM laboratory experience, students choose from a variety of samples programmed into the simulation. Students are then required to follow all the regular procedural steps to prepare the sample such as mounting it on the sample stage, and running it through a virtual sputter coater. A developmental screenshot of the SEM sample stage and chamber are shown in figure 6. Once sample preparation is complete, students must vent the SEM chamber, mount the stage, and close the chamber. Students then use a VR computer (see figure 7) to pump down the chamber and begin imaging the sample.

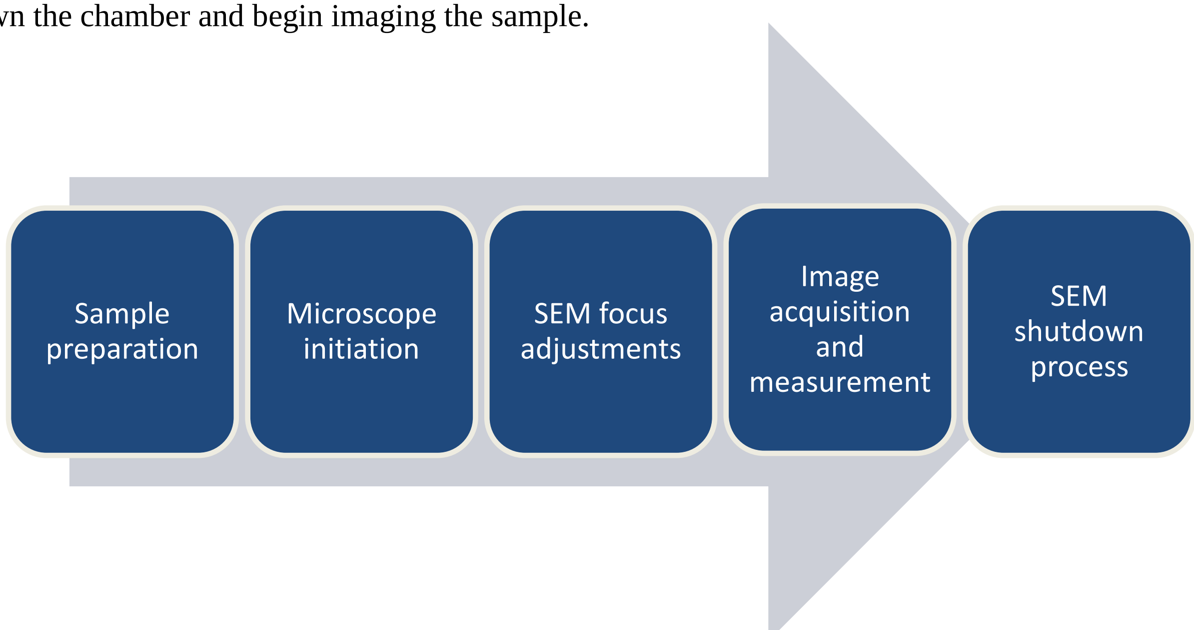

Figure 5: Steps of VR SEM Procedure.

During the imaging process, students experiment with magnification, working distance, brightness and contrast, beam intensity, and stigmator adjustments to get the clearest image possible (see figure 3). Due to the nature of the VR lab, students are able to peer into the SEM chamber during the scanning process and watch the electron beam in action.

This enables them to visualize SEM functionality in a way that is not visible in the chamber view camera on a real SEM. If appropriate safety protocol is not obeyed, the virtual sample stage runs into detectors or the sides of the chamber, and the simulation alerts the student that damage occurred. Once the image quality is optimal, students must acquire the image and use the VR computer to take measurements of image features. When measurements are complete, students can repeat the process with a new sample or remove the sample and procedurally shut down the SEM.

Through this process students prepare themselves to use a real SEM later on in the module. If mistakes are made, no real damage occurs, and students can repeat the experiment until they are able to complete the procedure without incident. In addition, use of the VR SEM familiarizes students with SEM controls and image adjustment procedures so less time is required to master these controls on the real SEM. Figure 8 shows a student exploring the VR SEM room during VR lab development.

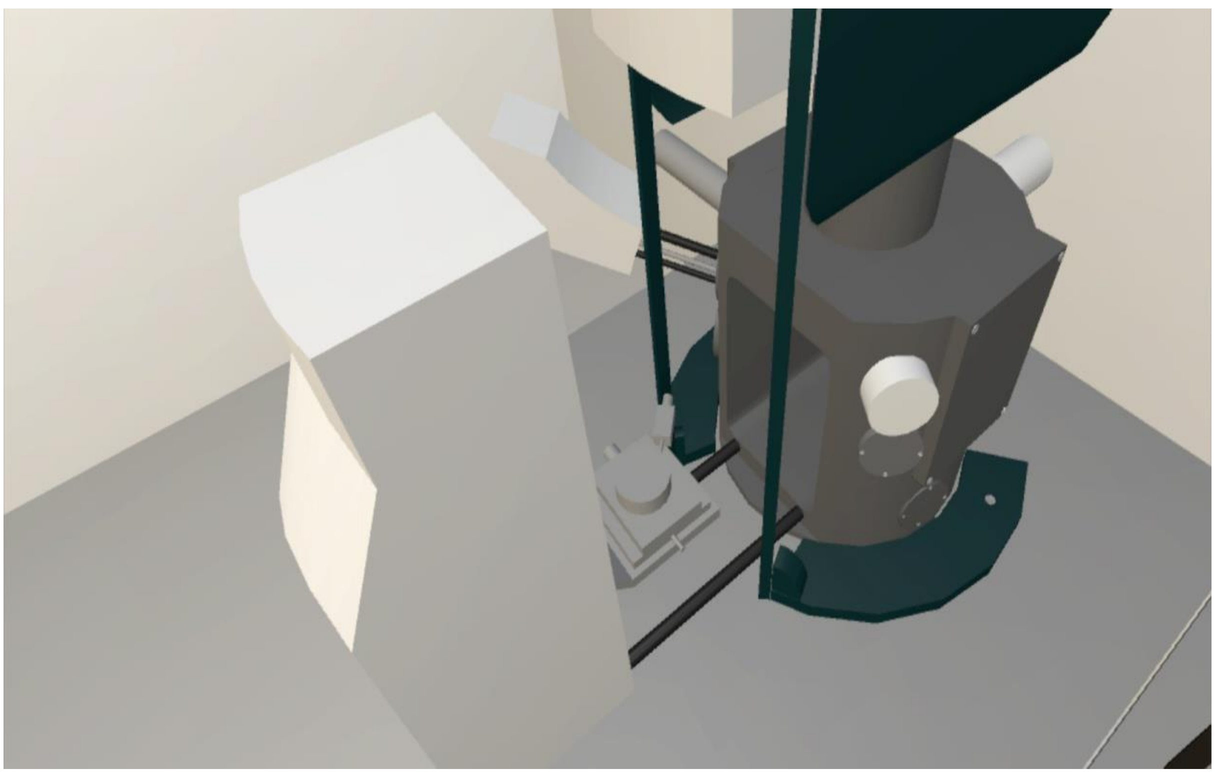

Figure 6: Screenshot of Stage and Chamber in VR SEM

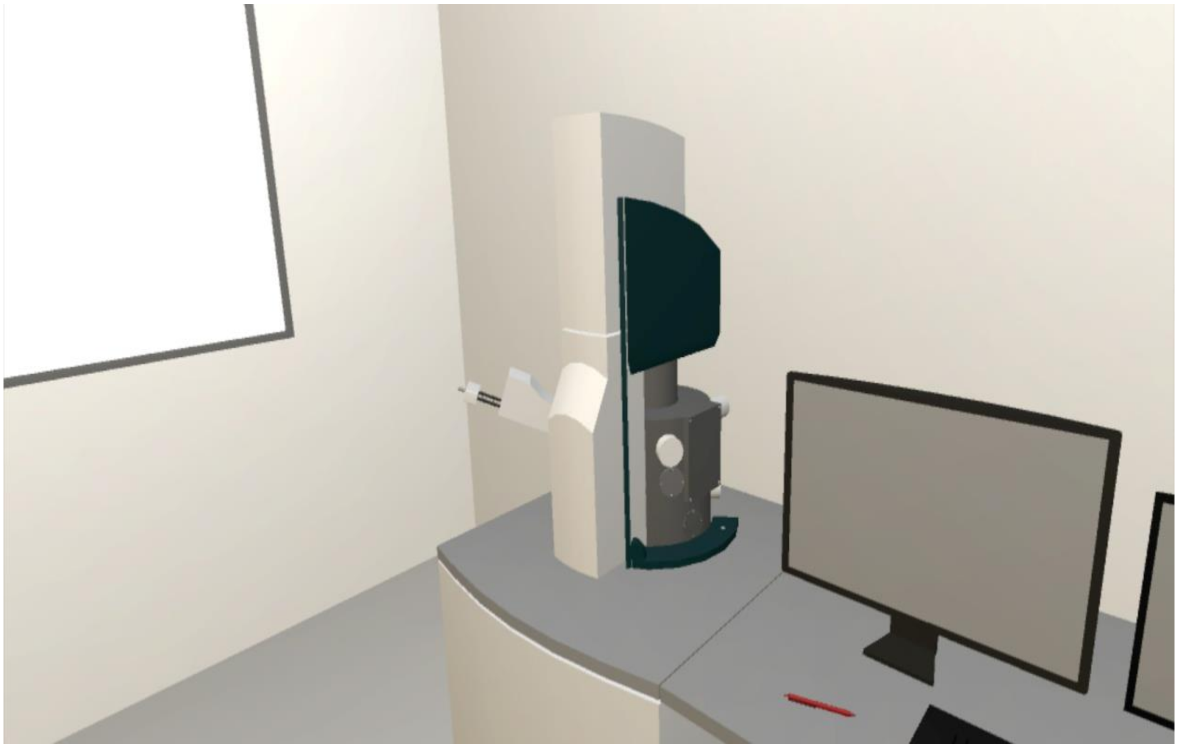

Figure 7: Screenshot of SEM VR Lab Displaying Microscope and Associated Computer Display.

The VR SEM laboratory is designed to supplement or even replace use of a real SEM in institutions that cannot afford a fully equipped SEM laboratory. Use of VR controllers enables the students to interact with the virtual environment in much the same way they would in the real SEM laboratory. For example, a student preparing to use the VR SEM is required to turn on and regulate nitrogen flow from a VR nitrogen tank prior to using the microscope. In order to accomplish this, the student must locate the tank and turn the flow valve using a twisting motion of the controllers. Other aspects of the VR lab are controlled in similar fashion. This provides a learning advantage over simply watching a simulation because students are required to do the experiment themselves using physical movements similar to those used in the real world. As a result, they learn the procedure by performing it, and will have better recollection of SEM imaging procedures when required to use a real SEM later on.

In order to gauge the efficiency of the VR laboratory in teaching students correct lab procedures, a group of 12 students was introduced to the VR lab and asked to complete an experiment. The 12 students were selected from UVU's computer science, computer engineering, electrical engineering, and animation and game development departments to ensure they had decent experience in using computer based systems. Most of the students had little or no knowledge of SEM and nanotechnology fabrication procedures prior to testing, and no additional SEM or nanotechnology development education was provided. In this way, the VR lab in-game instructions became the sole source of information for students being tested. After the VR simulation was complete, students were given a six question survey to assess their experience

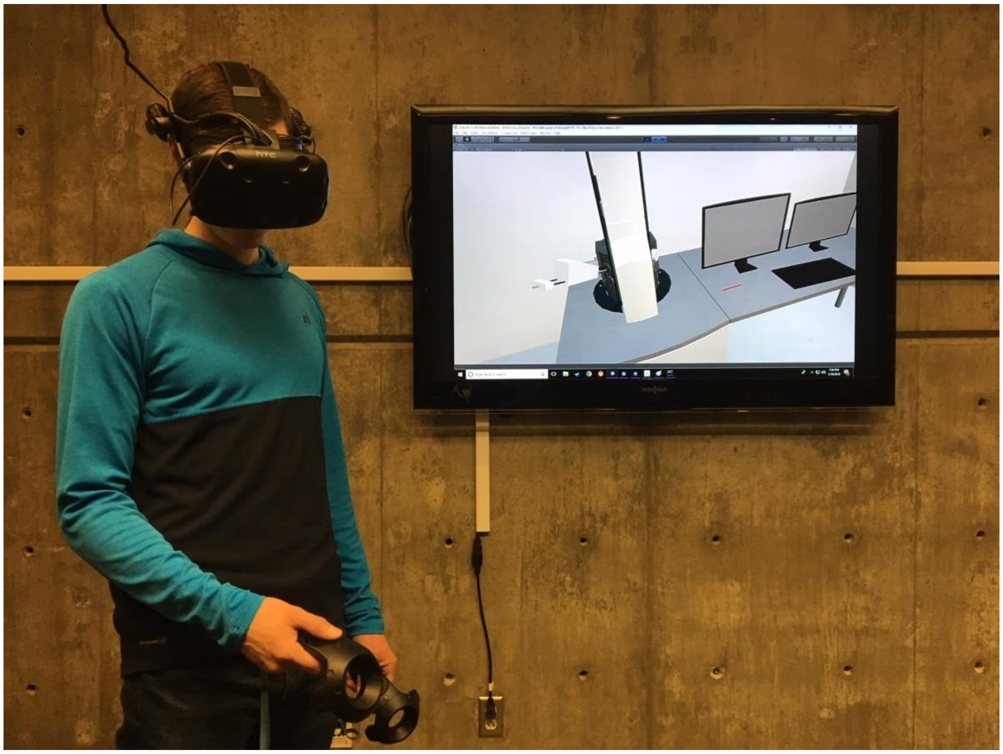

Figure 8: Student Exploring SEM VR Lab.

with the VR experiment. Observations and survey data are explained in detail in the results section of this paper.

3.4 Using a Real SEM

The fourth phase of the SEM module incorporates student use of a real SEM. Once students prove they can safely and successfully use an SEM in the VR lab, they are permitted to use a real one in an SEM laboratory. In this phase, Tescan's Vega3 SEM was used, and students were required to use the secondary electron detector to perform imaging of a sample. Students are closely monitored during this step of the module to gauge their understanding of using an SEM and to ensure no equipment is damaged. Students are provided a set of instructions to help them complete an SEM imaging experiment with a sample of their choice.

Lab instructions for the SEM experiment were constructed by a team member in UVU's physics department. To test the clarity of SEM lab instructions prior to implementation, three students from the nanotechnology team were given the opportunity to enter the lab and run an experiment with a sample of their choice. Each student was given a set of instructions to guide them through the entire SEM procedure. The experiment required students to prepare the microscope and samples, use image adjustment features to get a clear image, and acquire and measure image features before shutting down the SEM. During the imaging process, students were required to use each of the imaging adjustment features (working distance, magnification, etc.,) in order to form a clear image. Student questions and feedback were then used to improve and clarify the lab instructions. Figures 9-10 display images acquired by students in UVU's SEM lab that exhibit image adjustments for magnification and brightness.

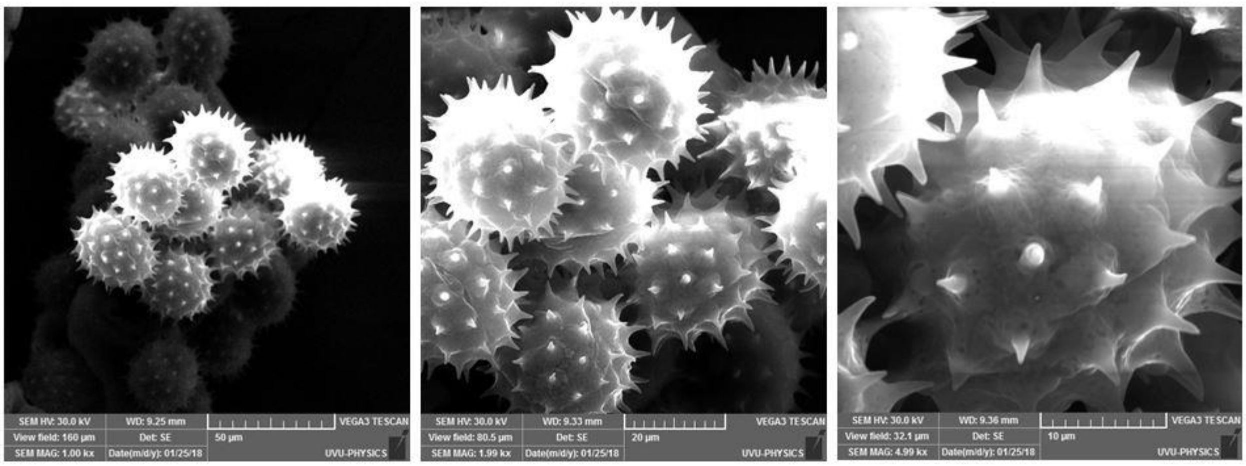

Figure 9: SEM Image of Pollen at Magnifications of 1000x, 2000x, and 5000x Respectively.

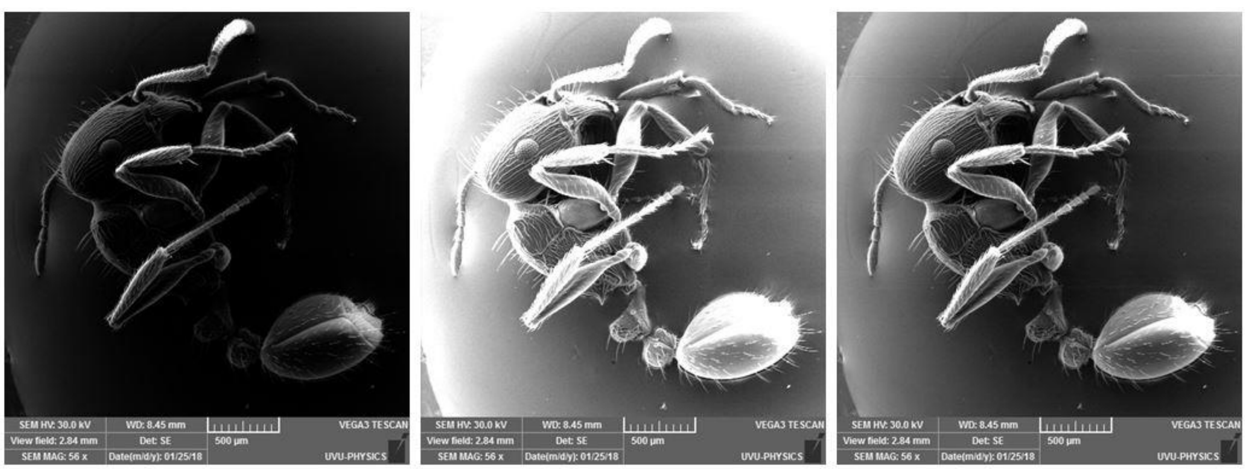

Figure 10: Brightness Adjustments for SEM Image of Ant. Left and Middle Images Show Sample too dark and too Light, with Optimal Lighting in the Image on the Right.

4.0 Results

As stated previously, the VR laboratory was tested by a group of 12 students in order to gauge its effectiveness in teaching students experimental procedures. Students were then required to fill out a six-question survey to assess their experience with the VR simulation. Survey questions and student feedback are presented in the following points.

What did you like about the VR system?

- It was nice to be able to get to know the process without having to worry about breaking expensive equipment.
- It was well programmed and very realistic.
- How immersive it was, and the teleporting.

What did you dislike about the VR system?

- Getting used to controls, reading fine text.
- It can be confusing to manipulate sometimes. Can be disorienting if not used to the teleporting system.
- I was confused where things were located. It took a while to get used to the grip controls.

Do you feel that interacting with the virtual reality lab helped you understand the experiment process better than simply watching a simulation? If so, how?

- Performing tasks got the process a lot more engrained in my head. I was able to repeat most tasks accurately the second time around.
- Definitely. It's a lot easier (in my opinion) to learn by doing.
- It's one thing to have someone explain the system to you. It's another to thing to actually (virtually) do it.

Do you feel you could repeat this experiment in the real lab after performing it in the virtual lab?

- Yes, if the buttons are all in the same place (labeled if different).
- Probably not perfectly, but yes.
- Yes. Tactile skill in reality obviously offers an advantage over VR. It would likely be easier in reality after experiencing VR.

What was the most difficult part of performing an experiment in the virtual laboratory?

- Reading, there were a few buttons that were hard to activate.
- Using tools, picking and placing objects, and moving by teleporting. I'm sure it becomes easier with ample experience.
- Locating machine controls.

What was one thing you learned as a result of performing this experiment in the virtual lab?

- Following instructions/procedures is just as important in VR as in real life.
- VR can be very similar to performing an experiment in the lab.
- I wish I could put my senior project in VR.

Out of the 12 students tested in the VR lab, 8 said they felt they were ready to perform a real laboratory experiment after the test, and the remaining 4 felt like they could do so if granted additional time in the VR simulation. The main concerns students had with the VR laboratory involved becoming familiar with the controls and VR navigation. Students who referenced these issues stated that additional time in the VR simulation could negate these effects. Development and testing of the VR SEM simulator is still underway, and more data will be needed in order to prove that the VR SEM can fully prepare students to use a real SEM. Results so far provide positive evidence that the VR SEM is an effective method for preparing students for future SEM use.

5.0 Conclusion

Understanding how to correctly utilize and operate an SEM is essential to modern innovation and technology development. As the technology industry continues to reduce component size in integrated circuits and other microelectromechanical systems, scanning electron microscopy and its counterpart, electron-beam lithography, continue to provide the most suitable means for nanotechnology fabrication. The VR SEM module enables students to learn and practice scanning electron microscopy fundamentals in a way never before possible, allowing them access to a learning environment that enhances understanding and inspires innovation. Through the learning material and tools developed by UVU's nanotechnology team, students gain a greater appreciation for the applications of the SEM and its functionality, as well as hands on experience in a VR lab and with a real SEM. The program also provides a way for institutions without needed resources for an SEM laboratory to teach students SEM functionality and provide them with crucial experience needed to join the engineering workforce. It is hoped that dissemination of the VR SEM program and its related components will enable a wide range of colleges and universities to train the next generation of nanotechnology engineers.

Acknowledgements

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