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Recent Advances in VR Labs for Use in STEM Education

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Abstract
Virtual Reality (VR) is increasingly being used in the gaming and entertainment sectors. It has also been gradually finding its way in the industrial training sector. But its potential in the education field has yet to be fully recognized. Recent breakthroughs have made head-mounted displays (HMDs) for virtual reality (VR) accessible to the educational institutions and to the public at a low cost. Similar breakthroughs are on the horizon in the haptic gloves technology, which are likely to lead to low cost and functional haptic gloves. Combination of VR with haptic gloves is expected to significantly change the user experience for the better. This paper seeks to explore the untapped potential of VR technology in education, specifically focusing on its applications in STEM laboratories. After a review of our past work in the development of VR labs for STEM subjects, we will describe recent advances made in the development and implementation of VR STEM labs in engineering.

Keywords: *virtual reality; STEM laboratories; head-mounted displays; haptic*

1. Introduction

Innovative technologies are increasingly contributing to the teaching and learning missions of K-12 and higher education. One group of such innovative technologies is comprised of "*virtual reality*" and 3D gaming technology. VR's niche, in our opinion, at the high school and university levels is more in visualization and in supplementing practical experiences—as in lab courses—via video-game-like modules rather than in imparting abstract concepts. Pedagogical benefits of various forms of VR applications in education (both teaching and learning) and training continue to be evaluated and debated (Mayer et al., 2023). Matovu et al. (2023) reviewed a range of VR studies—a total of 64 that appeared over 2016-2020—on the teaching and learning of science. Makransky et al (2019) suggested that adding immersive VR to a science lab simulation lead to more *presence* but *less learning*. They also suggested topics that are more suitable for VR-based education than others.

While the use of VR technology has been maturing for courses that rely on, and benefit from, extensive 3-D *visualization* (such as human anatomy), its use to support the *laboratory* experience in STEM courses is still maturing. We believe that XR (collectively referring to VR, AR and MR) technology, if appropriately deployed, holds substantial potential to significantly enhance (supplement) students' lab experience. Not only does this potential exist in existing state of the XR technology, rapid improvements in XR and associated technologies, such as AI and machine learning, haptic gloves, etc., stand to improve the overall student learning experience even more significantly.

Several virtual labs have been created in the Virtual education and research laboratory (VERL) in the Department of Nuclear, Plasma, and Radiological Engineering at the University of Illinois, representing various experiments in the undergraduate curriculum. These include a calorimetry lab to measure the specific heat of metal specimens, a shielding lab to measure the attenuation coefficient of shielding material, a chemistry lab for safety training, and a radiation lab to measure the half-life of radioactive substances (Karancevic et al 2004; Dixon et al, 2007; Haddish et al, 2013; Satoh et al, 2015; Rizwan-uddin, 2018).

Before we describe recent developments, we first in the next section briefly describe the state of technology in the field of XR. This will be followed by a description in Section 3 of two of the virtual labs developed by our group. In Section 4 we describe the most recent advances introduced in these and other virtual labs. Our ongoing and future work is described in Sec. 5.

2. Brief overview of VR technology

VR hardware over the last few decades has evolved rapidly, as has the software for application development. Rapidly changing technology has necessitated new terminologies. Matovu et al (2023), for example, used the terms "*desktop virtual reality*" (DVR) and "*immersive virtual reality*" (IVR). This distinction has partly been necessitated by the simplicity with which a generic 3D model developed in one of the development platforms (Unity, Unreal, etc.) can be easily compiled for use on desktops, in immersive HMDs, and on smart phones. Hence, in any discussion of VR applications it is important to keep in mind the hardware on, or in, which the 3D model is to be experienced. The experience may or may not be immersive. The hardware include: desktop computer with a keyboard and a mouse, touchscreen tablet, cell phone, cardboard box with a slot for a cell phone, HMD, and AR device such as a *HoloLens*. These are shown in Fig. 1.

Fig. 1. Hardware for 3D models, DVR, and IVR display

Fig. 2. Devices to interact with 3D VR models

The major difference in these platforms is not only the "view", but also the way user interacts with the virtual model and manipulates objects in it. The entire keyboard and mouse are available for interactivity on a laptop or desktop. Interactions on a touchscreen tablet or a cell phone take a different form. Ways to interact with objects in a cell phone are limited. Smart phones, however, may provide interaction modes not immediately available on a desktop, such as tilt or turn. Interactions with objects in a 3D model in a HMD device is through a controller. The physical shapes of these controllers change rapidly from one model to the next. Controllers have a few keys, knobs (mini joysticks) and triggers. Note that these controllers can also be used with desktop and laptop computers. The controller-driven actions can be displayed in the digital model as human hands performing actions such as pressing a key or grabbing an object. Most advanced of these interactivity modes is via a haptic device, usually a glove. A haptic glove may not only allow the user to interact with the digital world in the same way one interacts with the physical world, it may also provide the sensation of touch to the user. Figure 2 shows the devices that can be used to interact with the digital world in DVR or IVR on, or in, different platforms.

Interactivity in VR over the years has been slowly improving. As an example, consider an action such as pouring water from a jug into a measuring cup. Such actions (interactivity) in VR labs executed on desktops are performed using the mouse and the keyboard. With touchscreen monitors, fingers can also be used to manipulate objects. In immersive version of these labs (conducted in a head mounted display (HMD) setup), interactivity is via an HMD *controller*.

3. VR Education labs

In this section we briefly describe two STEM labs developed in our group. These labs have been developed and tested on various platforms (Fig. 1) and using different devices for interactivity (Fig. 2). Simple models based on the physics of the experimental setup are coded in the STEM labs to evaluate the numerical values of the quantity to be measured. These mathematical models get their input parameters interactively from the users of the VR lab.

Fig. 3. Side-by-side comparison of a 3D model (left) and its physical counterpart (right).

A model of a physical lab space in our department was developed first. Figure 3 shows a side-by-side comparison of the 3D virtual model (left) and a picture of the physical lab (right). Having a virtual model of a physical lab is expected to help those students who will eventually do some of the experiments in that physical lab, and only supplemental labs in VR. For those students who will have no exposure to a corresponding physical lab (if one exists), there is likely to be no benefit of similarity between the physical and virtual labs. Lab has virtual models of apparatus needed to conduct the experiment. These devices may have buttons, switches, knobs, and digital data display windows. Some of these knobs and switches in these virtual models are "*live*", i.e., a user can use them to turn the equipment on or off, or set parameter values (by clicking). Data are displayed in either digital display windows or on a virtual computer monitor. Step-by-step instructions appear at the bottom of the screen.

3.1. Calorimetry Lab

The virtual calorimetry lab is designed to measure the specific heat of metals. This laboratory has virtual instruments (like a scale and hotplate) and virtual monitors. Virtual instruments in the model are interactive and can be moved and/or operated by the player. For example, the metal specimens in the experiment can be moved. When a specimen is placed on the scale, the virtual scale displays its weight in its digital window. Thermocouples can be connected to objects. Step-by-step instructions can be displayed through GUI. In the virtual lab, the student first walks into the lab. TA walks in and sets up the experiment table. The student then starts the virtual experiment. Experiment is conducted as follows:

1) Identify the equipment to be used in the experiment; **2)** Measure specified amount of water; **3)** Measure the temperature of the water; **4)** Pour the water in the inner tube of the calorimeter; **5)** Weigh the specimen; **6)** Pour water in a beaker; **7)** Place the beaker on the hotplate. Boil the water; **8)** Place the specimen in the water to bring it to 100 C; **9)** Attach thermocouple to the specimen; **10)** Place the specimen in the inner tube of the calorimeter; **11)** Close the lid; **12)** Observe the water and specimen temperature on the monitor; **13)** Stop the experiment when the two temperatures are nearly equal. Note the final temperature; **14)** With known water mass, specimen mass, specific heat of water and the final temperature, calculate the specific heat of the specimen. Figure 4 (left) shows the setup of the calorimetry lab.

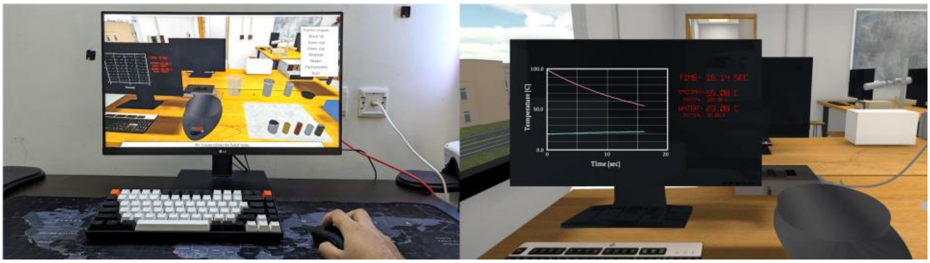

Fig. 4. Calorimetry lab on a computer monitor (left), and zoomed view of the virtual monitor showing temperatures as a function of time.

Note that in this version, the lab is expected to be conducted in DVR, using the keyboard and mouse. For example, clicking on the beaker filled with water moves it to the hotplate. Clicking on the knob turns the hotplate on. Clicking on the thermocouple connects it to the specimen, and so on. The physics model coded in the virtual model is used to calculate the temperatures of the water and the specimen as a function of time. The temperatures of the specimen placed in the calorimeter and of the water in the calorimeter are displayed as a function of time on the computer monitor, as shown in Fig. 4 (right). Students wait till the two temperatures become nearly equal. This equilibrium value is noted down and is used to estimate the specific heat of the specimen. Experiment can then be repeated for other specimens.

3.2. Shielding lab

The player in this virtual lab can measure the attenuation coefficients of different shielding materials. A screen shot of the virtual model is shown in Fig. 5. Users can manipulate shielding blocks made of different materials, place multiple blocks between the radiation source and the detector, thus effectively changing the thickness of the shielding material, and operate the radiation measurement equipment.

The student *clicks* on the shielding blocks placed on the table, which moves them next to a scale, allowing the student to measure their thickness. Next, clicking on the block moves it to the space between the radiation source and the detector. Counts can then be measured by setting the time interval (by clicking on the required buttons) and clicking on the counter button. The process is repeated for different numbers of shielding blocks, thus obtaining data for different thicknesses. The entire process can then be repeated for blocks made of different materials. The physics model is based on the attenuation model *($e^{-\mu\Delta x}$)*, where Δx is the thickness of the shielding material. The count data displayed in the virtual LED display is realistic and can be used to estimate the attenuation coefficient of the shielding material. Figure 5 shows two of the shielding blocks placed in between the radiation source (on the left) and the detector (on the right). Other shielding blocks (C, D and E) are placed on the table. Collimator blocks and the detector can also be seen. Detailed steps to execute this virtual lab are omitted here.

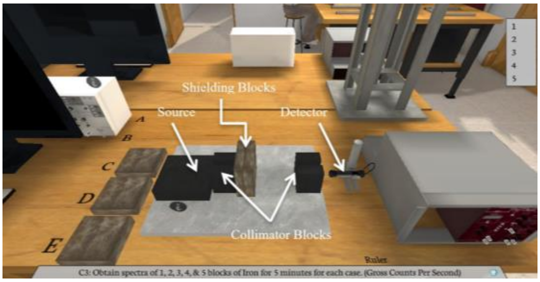

Fig. 5. 3D model of the shielding lab

4. Recent developments in STEM VR Labs

As mentioned above, the early models of the VR labs have several limitations. Some of the improvements over the last few years are described in this section. Most of the improvements have been to make the visual as well as the user interaction more realistic:

1) Rather than a single-click action, when an object is to be moved, we now can grab the object by clicking on it, and then moving it to the spot where it needs to be placed. **2)** Pouring water in a beaker is now a more realistic experience with appropriate motion and tilting of the hand. **3)** Wires and wire handling is now much more realistic. (In the older version, a single click connected a wire (such as a thermocouple) to its intended location.) **4)** The VR lab now allows users to *manually* connect wires to ports or objects. The user in the new version can "grab" the tip of the wire and then "insert" it at the desired port or on the object where it needs to be connected. **5)** As the water temperature reaches boiling point, bubbles appear in the beaker. **6)** All the apparatus and their functions are to be identified before starting the experiment by clicking on them. **7)** Additional videos have been embedded for on-demand instructions.

In addition to these, three other major developments are described in more detail below.

The first is the extension of these VR STEM labs to be conducted in the immersive environment of a HMD, and operated using a game controller, instead of by using the mouse and keyboard. 3D immersion makes the lab experience more realistic, and the game-controller-based operations provide an improved level of interactivity. Another significant achievement was attained through enhanced haptic feedback using the new Quest controllers. By leveraging the *Virtual Grasp API*, objects can be held using both hands, and can also be tilted. Two-handed operations include steps such as tilting a water jug held in one hand and pouring the water in a beaker held by the second hand. An example is shown in Fig. 6 (left). Sensation of different weights when using the game controller can be replicated using strong or gentle haptic vibrations. Though the player is using the VR controller, the actions are shown in the HMD (or on the computer monitor) being carried out by two virtual hands. This is shown in Fig. 6 (right).

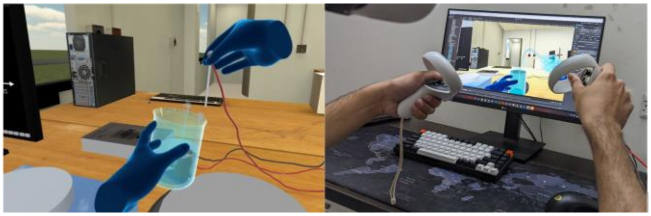

Fig. 6. Sensation of weight through haptic feedback(left) and two handed operation using VR controllers(right).

The second and third major recent developments are those of the development of virtual 3D models of two new physical facilities. The (physical) undergraduate lab in NPRE has recently been moved to a new facility. With the benefits of the virtual model being similar to the physical space in mind, a virtual 3D model of the new physical facility has been developed. Using pictures of the actual facility to extract textures, the detailed 3D model of the physical lab resembles the physical lab, and improved lighting further enhances immersive feeling. A side-by-side comparison is shown in Fig. 7.

We have also developed a 3D model of a new (physical) reactor simulator lab. This simulator lab mimics a reactor control room. The lab has a classroom setting and glass-top simulators. This simulator room is designed for training and evaluation of human responses in various scenarios in a nuclear control center. The corresponding 3D model (Fig. 8 illustrates a side-by-side comparison.) and the VR capabilities of this lab can be used to supplement training in the physical control room, for design alterations of the control room setting, human factors studies, and for tracking of control room operator actions through HMDs eye-tracking feature.

Fig. 7. Side by side comparison of the new lab (left) with its visually improved virtual model (right)

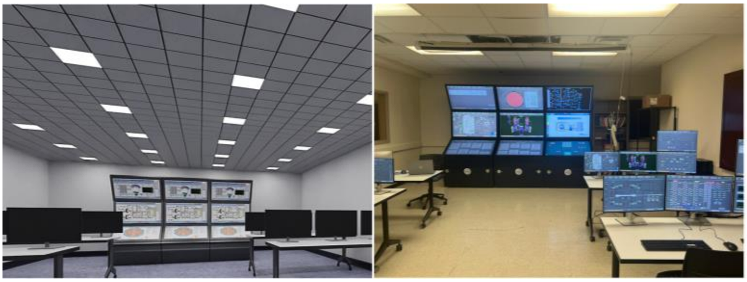

Fig. 8. Side by side comparison of control room simulator lab (right) and its virtual model (left)

5. Ongoing and future work

The use of VR in STEM lab education, and XR technology in general, is still in its infancy. With new technological advances constantly on the horizon, VR lab experience in STEM fields is likely to continue to improve. Several areas need improvement. Pedagogical assessment of STEM VR labs is also needed. Our current focus is, in addition to the general improvement of the VR experience using currently available technology, on exploring haptic gloves for improved sensation and more realistic operational experience. Haptic gloves, by simulating tactile sensations, offer a nuanced and responsive touch interface. They will allow the students to interact with virtual experiments, manipulate objects, and experience a heightened level of engagement in educational activities. This evolution not only will enhance the sense of presence and interactivity but will also facilitate a more intuitive and hands-on learning experience. We also plan to implement VR labs in courses and use systematic assessments to evaluate their efficacy in engagement, learning, and retention.

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