Next Generation Nuclear Engineering Education and Training using Virtual Labs

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INTRODUCTION

The United States is on the precipice of a surge in deployment of nuclear technology, the likes of which have not been seen since the 1960s. However, human capital development remains an issue for the nuclear workforce due to the aging of current industry professionals[1]. As newly minted engineers begin to contribute to the nuclear sector, they will be called upon to utilize new technical skills in ways their predecessors were not. It is imperative that students learn the most effective ways to use this technology to enhance their understanding, skills, and capabilities.

Unfortunately, fewer and fewer nuclear facilities remain available across academic institutions with nuclear engineering programs. The costs, both monetary and regulatory, of maintaining nuclear education spaces are rapidly increasing. This places an upper limit on the pool of interested students and excitement about the field, since one lab can only support a finite number of students. This trend was only exacerbated with the recent COVID-19 pandemic. The lack of accessibility of nuclear engineering laboratory experiences could make it harder for universities to build large and healthy nuclear departments. Further, certain fundamental concepts can never be safely performed at a real reactor, e.g., accident scenarios, and certain core concepts in nuclear engineering are gated behind years of experience and licensing procedures in order to be taught safely, such as reactor operation. To reach a wider range of potential students for easier and less expensive access to nuclear engineering knowledge, virtual labs could be a promising alternative as a replacement for in-person labs. This could save valuable reactor time as well as reducing the need for heavily regulated neutron sources[2].

In this paper, we present an effort to address this challenge by developing high fidelity, real-time nuclear-based Virtual Laboratories as a means of enriching hands-on laboratory activities and providing more opportunities for students to interact remotely with equipment not feasible otherwise. In these virtual labs, students are trained to (i) detect and measure dose rate, gamma ray spectra, and fast and thermal neutrons emitted from various radioactive sources, and (ii) explore a wider variety of reactor concepts and operation scenarios and practice reactor operation not feasible otherwise (currently only a licensed reactor operator can operate at the reactor console – students only observe). This is a multidisciplinary effort that brings together nuclear engineers, reactor operators, faculty, undergraduate and graduate students and computer science and computer vision researchers. For example, all three of these labs have been developed with the help of the Purdue EnVision Center, which has been handling the lab visuals and interfaces. The virtual labs will be deployed as part of the Nuclear Engineering Undergraduate and Graduate Lab courses.

VIRTUAL LAB PRODUCTION PROCESS

In the design process for the virtual labs, we have adopted a development and testing methodology to best target the learning experience modeled after Kolb's Experiential Learning loop[3]. In the experiential learning loop, students are allowed to interact with the learning platform to have concrete experiences and adjust their interactions in future experimentations that would allow engaging self-paced learning opportunities. The structure follows a development, testing, feedback, and ideation loop (Fig. 1). This agile development pipeline allows for further flexibility in the implementation while also ensuring the key learning objectives are tackled as a part of the virtual experience.

In simplifying the data simulation and integration of the resulting output into the virtual lab, this project is leveraging online web services for on demand computing. This allows the virtual labs to directly communicate with a computing node to generate the data to offload the computing requirements while keeping the virtual lab accessible via a light-weight web environment. As a part of these lab, the students will be able to navigate the setup and use the lab equipment in a safe environment by interacting with the sensing and diagnostic equipment, e.g., detectors and oscilloscope. Within the virtual labs, the students will be able to select each of the appropriate equipment and connect the components to begin testing for signal while calibrating the high voltage generator and validating through the oscilloscope.

VIRTUAL GM DETECTOR LAB

The virtual Geiger-Mueller (GM) detector lab simulates the operation of a GM counter. It allows a user to choose one of four radioactive sources: Co-60, Na-22, Cs-137, and Ba-133 to measure radiation level with a GM detector at various distances and for different shielding materials placed between the source and the detector. For shielding materials, users have the options of concrete, wood, and lead, and their thickness can be customized. Especially, the lead and wood can be combined in either order to learn how to compute the total attenuation coefficient and how the order of materials affects the results. Users can change the source-detector distance, radioactive sources, and materials to determine the dose rate variance as a function of source-detector distance. Snapshots of the virtual GM detector lab graphical user interface (GUI) is shown in Fig. 2.

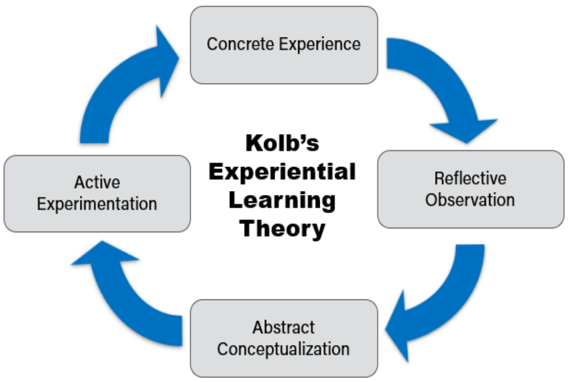

Fig. 1. Kolb's Experiential Learning Theory.

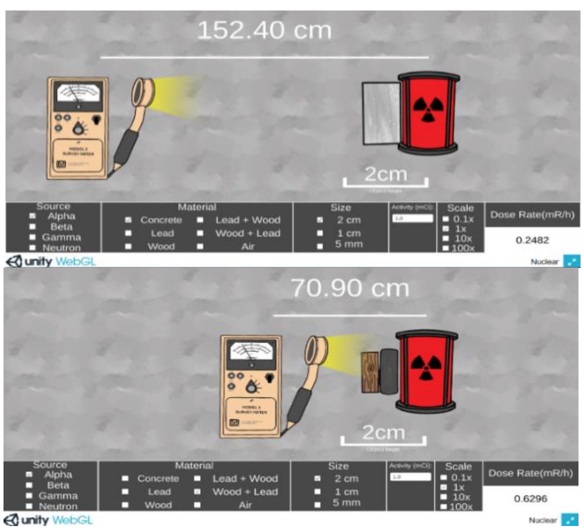

Fig. 2. Virtual GM detector lab build test with a 1 mCi alpha source and 2 cm of shielding concrete (top) or combination of different materials (bottom).

This lab primarily utilizes the dose rate equation and the gamma attenuation equation, both of which are shown below.

$$D_r(r) = 5.15 \times 10^3 \frac{CE}{r^2} \quad (1)$$

where D_r is the dose rate in mR/h, C is the activity in mCi, E the gamma ray energy in MeV, and r is the source-detector distance. The gamma attenuation equation is used to calculate a shielding factor which can be multiplied with the dose rate to find a measured dose rate behind the material:

$$I(x) = I_0 \exp(-\mu x) \quad (2)$$

where μ is the linear attenuation coefficient (cm^{-1}) and x is the thickness of material (cm), and I_0 is the initial intensity. Different attenuation factors are applied for each gamma and material combination. Gammas that have an energy below 0.1 MeV were not considered because their frequency is less than 10% of total decays. The gamma energies and attenuation coefficients were drawn from the NIST x-ray mass attenuation coefficient database[4].

VIRTUAL NEUTRON DETECTION LAB

This Virtual Lab aims to simulate a neutron detector and signal processing modules. We worked with two different gas proportional counters, He-3 and the BF_3. Neutron detectors are used alongside a preamplifier, the purpose of which is to simply amplify the initial pulse signal that the detector gives off when a neutron is captured. An amplifier, single and multi-channel analyzers, high voltage supply, and scaler-timer are needed to further process the signal[5-11]. The goal is to make the virtual labs as realistic as possible. The rendering process from actual real-world equipment to virtual lab is shown in Fig. 3.

The learning outcomes for this lab is to (i) create a count rate – voltage curve from collected data, (ii) identify the plateau, the optimal operating voltage, the total number of counts, the pulse height distribution, and full energy peak, and (iii) explain the differences in spectra and optimal operating voltage for different neutron detectors. To achieve this, the virtual lab would allow to (i) connect the various parts and operate a neutron detector, (ii) record and plot the pulse height spectrum for different neutron detectors types and sizes, (iii) select a region of interest in each pulse height spectrum and measure the integral counts for various operating voltage settings, (iv) plot the count rate vs. voltage setting.

Since the energy spectrum depends on the size of the detector, three different sizes are modeled, small, large, infinitely large, to provide the students with the opportunity to investigate various spectra that are expected in actual labs. The neutron interactions with the detector gas are modeled probabilistically and random noise is added to make the spectrum more realistic. As can be deduced from the spectra, in the small detector, the probability for the triton to be captured is the highest, resulting in it having the largest peak. In the large detector, the full energy peak is the largest peak out of the three peaks. In the infinitely large detector, only the full energy peak is shown because both triton and proton are 100% captured due to the detector's hypothetically large size (Fig. 4).

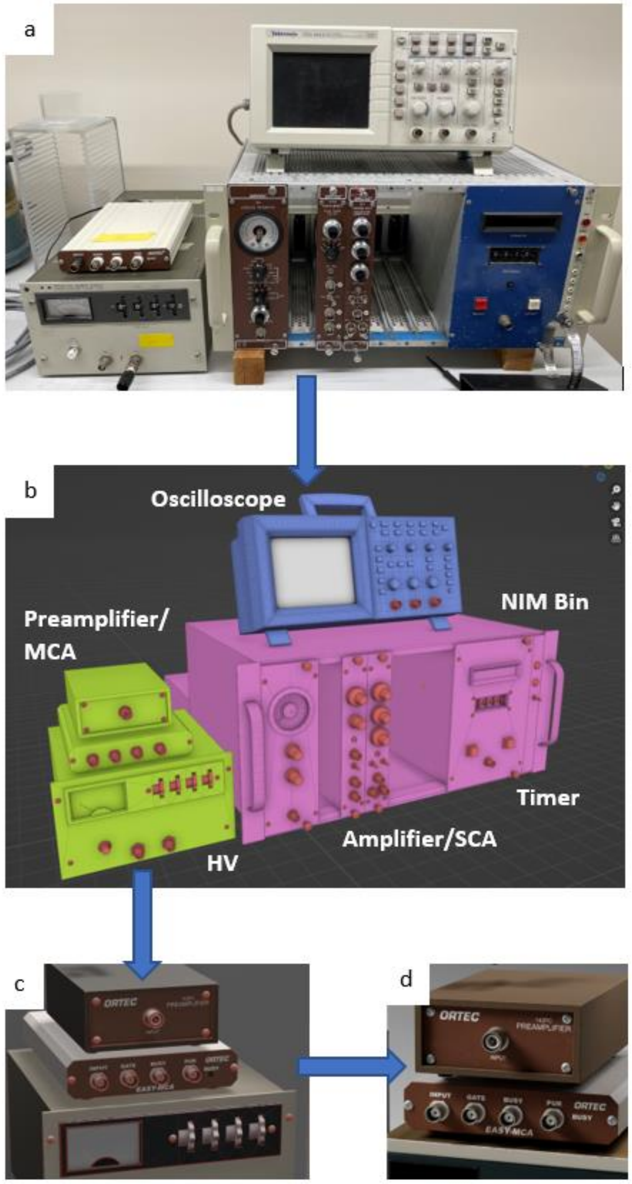

Fig. 3. Rendering process of neutron detection electronics equipment. (a) Actual equipment used for nuclear engineering labs; (b) rendering; (c) texturing; (d) final artwork sample.

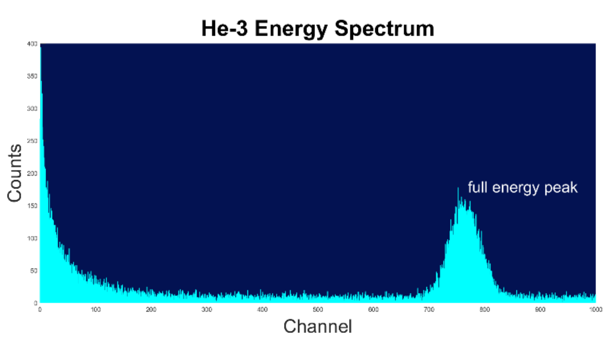

Fig. 4. Virtual Lab display of an infinitely large neutron detector spectrum.

VIRTUAL REACTOR LAB

This Virtual Reactor Lab aims to simulate reactor operation and is based on the Purdue University Research Reactor (PUR-1), which is a 10 kW pool-type research reactor with plate-type LEU fuel and three control rods (two safety shim rods and one regulating rod). The PUR-1 core is cooled via natural circulation and the neutron flux is monitored by 4 neutron detectors (1 fission chamber and 3 ionization chambers). The Virtual reactor lab focuses on simulating the nuclear reactor operation, instrumentation, and control. The main outcome will be the application of theory to operation and control of reactor systems. It will introduce the main features of a nuclear reactor including reactor control experiments (a concept that is rarely demonstrated in actual reactor settings) and will allow the students to perform measurements of kinetics parameters necessary to understand fundamental aspects of reactor physics such as neutron lifetime, delayed neutron fraction, and control rod worth. Finally, the Virtual Lab will culminate in hands-on operation of a full research reactor using PUR-1 (Fig. 5).

Fig. 5. The overview of PUR-1 facility, control console, reactor tour, and Cherenkov radiation glowing from the PUR-1 core.

A GUI was made to simulate the digital interface in the reactor operation room. The GUI was built in Unity environment. The reactor control options are built to be identical to the real control options. Fig. 6 shows screenshots of the virtual lab, which includes an interactive model of the PUR-1 reactor room. The reactor simulation calculates parameters such as neutron count rates, reactivity, coolant temperature, and shows them to the user as output graphs. The user can zoom-in on specific screens on the console and the data from the reactor simulations can be saved by the user to include in a lab report.

The reactivity calculation in the virtual reactor lab is developed based on the point kinetics equations and the reactivity insertions by the control rods are based on the real rod worth curves from the PUR-1 control rods and it is given by:

$$N(t) = N_0 e^{\frac{k-1}{l}t} \tag{3}$$

where N_0 is the initial neutron population, k is the multiplication factor, l is the neutron lifetime, and t is the elapsed time. The simulation is started with all control rods at their default position, and the reactivity insertions are governed by the movement of the control rods. In addition, the virtual reactor also includes realistic scram conditions so that students learn how the parameters (neutron flux, reactivity, and reactivity change rate) change when the reactor is promptly shut down. All codes determining the math behind the virtual reactor lab was originally built in MATLAB and then converted into C# by the Purdue EnVision Center.

Fig. 6. Screenshots of current PUR-1 Unity build: Reactor room (top), control interface (bottom left), control panel model (bottom right).

CONCLUSIONS

The use of virtual labs will help nuclear-related departments support more students and increase the availability of nuclear engineers and scientists. Separating education from the expensive and difficult to maintain nuclear facilities will help educational organizations teach more people about nuclear science. While virtual labs may not be a true substitute for in-person experiments, they can greatly improve the teaching capabilities of organizations that lack the resources for physical nuclear labs. All of the virtual labs detailed in this paper are close to completion, and upon completion they will be made freely available to help augment nuclear education efforts and spread nuclear education to more people

By combining mixed reality technologies with physics-based modeling and simulation and authentic 3D machine interfaces, the proposed virtual labs have the potential to provide interactive environments for creating and conducting simulated experiments and allow course content delivery with a more flexible access by learners to physical laboratory spaces and specialized equipment. Currently, these labs simulate fundamental concepts in nuclear engineering such as neutron detection, gamma detection, and reactor operation and are being built and are at varying stages of development. It is worth noting that the added value of a virtual lab, besides the decreased reliance on expensive equipment, is the option to include additional virtual features, e.g., warnings, pop up notes and manuals, not easily available in physical labs.

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