Enhancing Interactive Learning in Engineering Classes by Implementing Virtual Laboratories

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Abstract— **This work-in-progress paper describes the incorporation of two virtual laboratory modules as an interactive teaching strategy that enhances both remote and in-person learning. Teaching engineering classes online during the pandemic has shown us the values of in-person interaction and the versatility of information that can be conveyed in physical classrooms. Many types of teaching strategies, such as physical demonstrations and in-class activities, are more accessible in-person compared to virtual sessions. To address this issue, we introduce two virtual lab modules with (a) pre-recorded and (b) real-time models that provide platforms for virtual mechanical tensile testing and a remote photon quantum entanglement experiment, respectively. The first virtual lab platform was built from a host of recorded mechanical tests on several engineering materials samples. After choosing the experiment/material, students can simultaneously view the data acquisition and the video of the test in detail. The numerical raw data set for each specimen is accessible after completion of each experiment in form of a spreadsheet. The introduction of the virtual lab has allowed us to add interactive elements to solid mechanics and machine design classes. For the second virtual laboratory module, we present a real time lab platform, where the participating students can perform experiments and collect data in real time by accessing the lab setup remotely. The general concept of the real time virtual lab is based on a human-in-the-loop control system that allows a user to operate an actuator remotely. To feature this real-time approach to virtual laboratory, we selected photon quantum entanglement experiments as part of mechatronics class. The early results, drawn from the students' feedback, demonstrate the promising outcomes of the virtual lab platforms for students learning and instructor-student interaction. Participating students expressed high level of connection to the classes and conceptual grasp of the course topics. The results of this report point to new pedagogical approaches to enhance learner-instructor connectivity and experiential learning in the post-pandemic engineering education.**

Keywords—virtual laboratory, interactive learning, student engagement, student-faculty interaction, remote experimentation, digital engagement

I. Introduction

One of the most important lessons that we have learned during the 2020 forced transition to remote learning is the difficulty of adapting laboratory classes to online platforms. Furthermore, teaching engineering classes online during the pandemic has shown us that most types of interactive teaching strategies, such as physical demonstrations and in-class activities, are less accessible in remote learning. Our study is motivated by the need for interactive virtual platforms, where faculty and student groups can work together on engineering problems by experimenting and conducting investigative analysis of engineering topics. Such virtual modules will contribute experiential learning and establish a more effective correlation between theory and practice of engineering [1-3]. Additionally, being equipped with the option of a well-developed virtual lab will clearly boost the resilience of our STEM curricula, particularly in the events that physical access to university laboratories is limited due to unprecedented conditions, such as pandemic restrictions [4-7].

In the following sections, we describe our approaches to integration of virtual laboratories in engineering education, by introducing two virtual platforms for (a) mechanical testing of engineering materials (tensile test) and (b) a remote hands-on photon quantum entanglement experiment. The virtual tensile testing module is based on pre-recorded experiments and was implemented in solid mechanics and design of machine elements classes of 30 to 50 students in fall 2020 and winter 2021 quarters. The remote quantum entanglement module is based on real-time, remote actuation, and was introduced in a mechatronics class of 40 students in fall 2020. The study of the different modes of operation in these lab modules provides a useful perspective on applicability of virtual labs, versatility of their approaches, and benefits of integrating them in engineering education.

II. Pre-recorded Virtual LAb Module for Mechanical Testing of Engineering Materials (Methodology and Approach)

As the first virtual lab module, we discuss the implementation of tensile testing of engineering materials in *Solid Mechanics I* and *II*, and *Design of Machine Elements* classes. The platform used for this virtual lab module includes the prerecorded tensile test on several different material samples (including metallic, plastic, and wood specimens) with round or rectangular cross sections. After selecting the materials to-be-tested from the interactive platform, the students can view the pre-recorded progress of the tensile test on the screen. During the experiment, the virtual lab interface demonstrates the progress of load vs. displacement on the right window next to the video of the experiment, as shown in Fig. 1.

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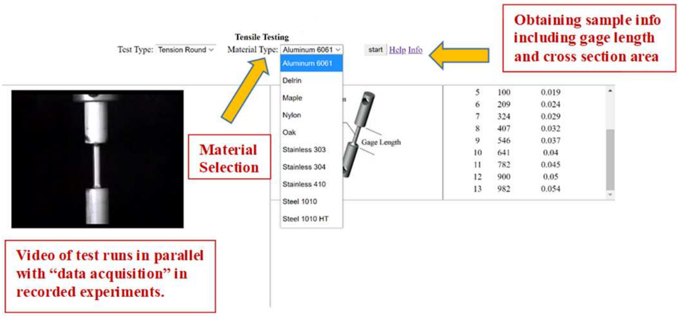

Fig. 1. Selection of sample material for tensile test on the virtual lab interface.

Upon completion of the test, the participants can download the data spreadsheet of the experiment from the platform. To provide a more realistic lab experience in the experiment, the data for each experiment is very slightly randomized. Therefore, even if the same experiment is selected the numerical results exhibit unique “noise”. Moreover, to recreate the experience of in-person experiments, the students will receive raw data and have to process it. For example, for the tensile test in the VLab, the students can download Force vs. Displacement data in a spreadsheet, which should be converted into stress vs. strain for subsequent mechanical characterization and analytic interpretation of the test.

a)

b)

Fig. 2. (a) Accessing experiment raw data after completion of the tensile test. (b) Progression of the steel 1010 tensile test highlighting different physical stages of tensile test, such as necking (middle image).

The participating students can obtain the specimen geometry (section area and gage length) from the sample information button in the virtual lab environment and schematics provided in the platform. Using a standard approach, they can then determine stress by dividing the load values by the sample section area, and determine strain by dividing deformation (deflection) values by the given gage length. Moreover, the students can see the videos of tensile test as the data flow develops and appears in the same timeline. This provides a more realistic experience for the participating students, as they can see different stages of each tensile test, such as necking phenomenon in ductile materials.

A. Classroom Integration.

During the solid mechanics classes, students often master how to follow the mathematical procedure for different solid mechanics equations. However, their conceptual mastery of the related mechanics topics is not on par with their computational skills [7]. This lopsided skill development often originates from asynchrony of mechanics theory and lab courses in most undergraduate engineering programs, or shortage of lab classes in engineering mechanics particularly during the pandemic. To address this issue, during the solid mechanics classes of 2020-21 academic year we extensively used VLab tensile test to visualize the fundamental concepts of stress-strain behavior, elastic modulus, yield and ultimate strengths, ductility, resilience, toughness, strain hardening, and the effect of heat treatment on mechanical responses of engineering materials. The students were able to see different stages of materials' behavior under tensile testing while listening to the related solid mechanics lectures. To provide a comprehensive understanding of materials mechanics, a host of materials including wood (oak and maple), plastics (nylon) and metals (different steels and aluminums) were virtually tested and compared during the class.

B. Implementation of Virtual Tensile Testing in Engineering Assignments.

In our curricular model, the implementation of the virtual platform evolved with the level of the engineering classes [7]. For a solid mechanics class, the students were tasked to run virtual tensile tests on select materials, collect and analyze the data, and determine samples' key mechanical properties such as modulus of elasticity, yield and ultimate strength, modulus of resilience, and toughness. For a solid mechanics II class, the students were given scenarios, where the 3D state of stress at a critical point of a structure (in form of a stress tensor) is provided. They were then tasked to use the virtual lab platform to determine (a) if selected materials can withstand the given complex loading scenarios and (b) factors of safety based on the different static failure theories (such as maximum shear stress and distortion energy theories) for selected materials under the provided 3D states of stress.

For Design of Machine Elements, the students were tasked to employ virtual lab tensile testing, to select a suitable material for round and square- section shafts - subjected to fluctuating loadings - based on the fatigue factor of safety theories such as DE-Goodman [8,9]. The assignment included real-life conditions of the shaft, such as surface finish, type of loading, shaft geometry, and reliability of fatigue analysis. The use of virtual lab for this assignment evolved [7], as the participants were assigned to determine endurance limit based on the tension tests ultimate strength to calculate both statics and fatigue (dynamics) factors of safety.

During the incorporation of virtual tensile testing, we gradually expanded the material, to be viewed, and the complexity of the related questions from the first quarter (solid mechanics I) to the second quarter (solid mechanics II and machine design) of implementation. One of our main challenges for implementing tensile testing virtual lab (and by extension other virtual modules in engineering), is the capacity to include numerous experimental details in the module. Some examples of such details in tensile experiment include the failure section (brittle vs ductile failure) and the formation of Lüders bands during the plastic deformation. To make sure students will pay attention to such details, we included questions/demonstrations of brittle and ductile samples and ask participants to explain their observations about the failure sections through mechanical failure and stress transformation theories. For including visually intricate details, such as Lüders bands in tensile tests, we recommend use of high-resolution cameras and professional photography/recording techniques.

III. Real Time Virtual Platfrom for Remote hands-on photon quantum entanglement experiment (Methodology and approach)

As the second virtual laboratory module, we describe a remote experimental setup, where the students have access to the lab setup remotely, and can perform the experiment and collect data in real time. The general concept of the real time virtual lab is based on a human-in-the-loop control system that allows a user to operate an actuator. The actuator acts as an intermediate tool that plays the role of a user in manipulating the required physical parameters of the experimental setup, and controlled by the students remotely. Therefore, any physical motion, which is normally required in setting up an experiment to change the experiment parameters in the laboratory, is achieved by suitably designed actuator systems.

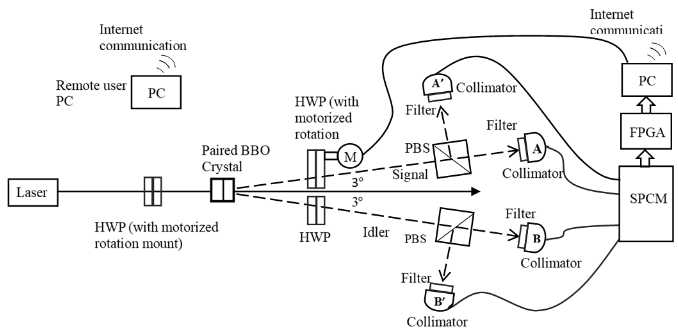

Fig. 3. Schematic of quantum entanglement experiment for remote lab module.

To feature real-time virtual laboratory, we selected photon quantum entanglement and quantum cryptography as an example of remote experiments. The remote module was implemented in the Fall 2020 for a mechatronics class of 40 undergraduate engineering students [10]. The schematic of the experimental setup is shown in Figure 3, where a motorized Half-wave plate is controlled by an electric motor remotely. The main components in this experimental setup include Half-wave plates (HWP), Motorized HWP, polarizing beam splitters (PBS), Paired nonlinear BBO crystal, a laser source, filters, collimators, and a single photon counting module (SPCM). Additional details of such experiments are available in references [10] to [15] where similar photon quantum entanglement and cryptography experiments are discussed.

The system physical setup is shown in Fig. 4. A video of the experiment, performed by students remotely, is available in [16]. A screenshot of the recorded video during the experiment is shown Fig. 5 On the right-hand side of this figure, the experimental results are presented using LabView software, which is connected to a FPGA and a four-channel Single Photon Counter Module. These results include single photon counts and coincidence counts. The students can see how the results are changing in real time. Like the virtual tensile test module, the experiment data results are saved in a spreadsheet file that students can access after completion of their experiment.

The motor control interface is shown on the left-hand side of Fig. 5. This interface allows entering a certain angle for the motorized HWP and rotate the HWP to a desired orientation. Therefore, the students who have the remote control of the laptop can enter any desired angle for the HWP and rotate it using the motor via this interface software. The figure shows a screenshot of a particular instance of the single photon counts and the corresponding coincidences during the online hands-on experiment. In this case, “A” and “B” are the single photon counts (in the range of 49,000), and the AB coincidences are about 285 counts, in this instant. The single photons are counted every 0.3 seconds in the setup shown, and the coincidences are counted for a window of less than 10 ns (7.8 ns for AB coincidences) of receiving photons by detectors A and B. A and B detect the photons with horizontal polarizations.

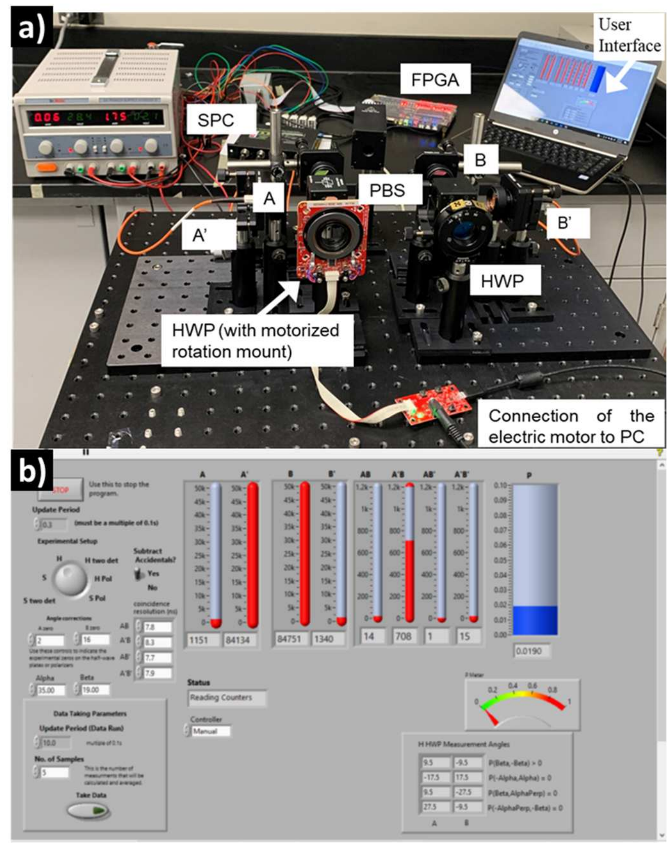

Fig. 4. (a) Physical experimental setup. (b) user interface of quantum entanglement experiment, showing the single photon counts (for A, A’, B, and B’) and the corresponding coincidences (for AB, A’B, AB’, and A’B’)

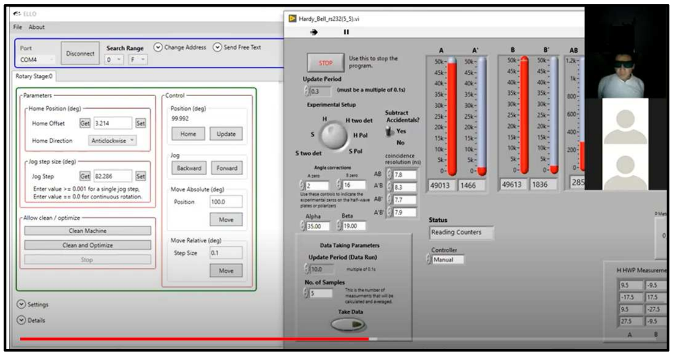

Fig. 5. A screenshot of the recorded video during the remote quantum entanglement experiment.

After the experiment was carried out by the students, a survey of the laboratory work was assigned to the participating students to measure the students feedback on performing such remote hands-on experiments. One of the questions in the survey was designated to evaluate the learning outcomes of remote experiments. In this survey, the majority of students agreed with the question "The remote quantum entanglement and cryptography experiments (as well as other remote online laboratory demonstration of various mechatronics experiments such as solar energy, fuel cell, automation, etc.) were helpful for understanding the topics effectively.", with 60% strongly agree, 35% agree, and 5% undecided. The list of all the questions and the details for the result of the students feedback (Fig. 6) are presented below:

1. The course stimulated my interest in mechatronics field.
2. The instructor effectively explained and illustrated the mechatronics course concepts.
3. The instructional materials increased my knowledge and skills in mechatronics.
4. The tests/assessments accurately assess what I have learned in this course.
5. This class has increased my interest in mechatronics field of study.
6. This course gave me confidence to do more advanced work in mechatronics.
7. I believe that what I am being asked to learn in this course is important.
8. This course enhanced my knowledge of mechatronics.
9. The remote quantum entanglement and cryptography experiments (as well as other remote online laboratory demonstration of various mechatronics experiments such as solar energy, fuel cell, automation, etc.) was helpful in understanding the topics effectively.
10. I would highly recommend the mechatronics course to other students.

The real time virtual quantum experiment presented in this paper was arranged mainly by the faculty instructors, and no specialized arrangement with the campus information technology professionals was required. The technical staff could support setting up the remote access experiments, when possible. One of the main challenges for this virtual lab is the limitation of the lab setup for a larger group of students. For this particular lab class, 40 students were accommodated. The physical setup needs to be scaled up to increase the number of active participants for larger classes. Another suggestion is forming student teams to perform the virtual test as a group, similar to other lab courses. It is important to note that real time virtual lab modules can be developed for most physical experiments by incorporating actuators that are controlled remotely. We plan to develop additional lab modules that can be accessed remotely by students. Remote virtual lab modules, in conjunction with in-person lab, will provide a desired level of flexibility for students and institutes, and enhance accessibility and digital participation in STEM classes.

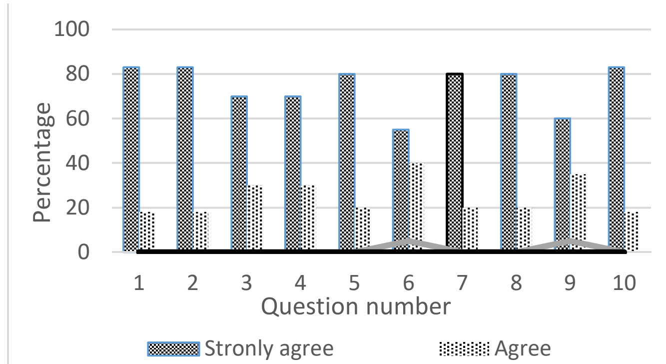

Fig. 6. Course Survey of Mechatronics class with remote quantum entanglement experiment.

IV. Concusion

This work-in-progress report highlights two platforms that we incorporated in the curricular models of solid mechanics, machine design and quantum engineering (within mechatronics) classes. To explore the potential and applicability of virtual labs, we implemented two approaches based on pre-recorded tests (asynchronous) and real time experimentation in the lab modulus used for solid mechanics and quantum engineering classes, respectively. The initial results of our study underline multiple benefits of virtual labs for engineering classes and - on a broader level - STEM education. First, virtual labs improve experiential learning and establish more effective correlation between theory and lab/practice of engineering. For example, our work suggests how virtual tensile testing can be incorporated into engineering mechanics to visualize and impact learning of several engineering concepts, including stiffness, strength, resilience, toughness, rigidity, ductility, fatigue failure, life-cycle analysis, reliability, and components design. Second, virtual labs contribute to interactive learning by providing common platforms, where faculty and student can work together on problem solving, and experimental analysis of engineering topics. Moreover, virtual labs providing flexibility to our engineering lab classes and experiential instruction. The need for such flexibility has been increasingly evident since the beginning of the pandemic restrictions, where in-person access to campuses has been very limited, and lab classes are negatively affected. Finally, virtual lab platforms enhance digital engagement and equitable education opportunities for student groups who otherwise will not have access to such higher-education programs.

For our future studies, we plan on expanding the scope of the virtual labs platforms to cover a series of well-defined engineering experiments that address different concepts in solid mechanics, dynamics, vibration, materials science, engineering design, and mechatronics courses. These platforms can serve as independent lab experiments or supplemental modules that may be used anytime in conjunction with in-person labs. We will also focus on a thorough assessment of student learning outcomes by applying a host of summative and formative evaluation techniques for each experiment on the virtual platforms. We hope that the results of this study pave the way for new pedagogical approaches that enhance student-instructor connectivity and improve the learning outcomes of engineering classes in the post-pandemic STEM education.

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