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OPEN-SOURCE VIRTUAL LABS FOR UNDERGRADUATE MECHANICAL VIBRATIONS AND CONTROL THEORY COURSES

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ABSTRACT

The vast majority of undergraduate engineering students struggle to acquire a deep understanding of complex topics presented in mechanical vibrations and control theory courses due to their highly mathematical nature, limited resources on the use of commercially available turn-key laboratory equipment, and lack of innovative teaching tools to improve student understanding. In this study, we developed open-source stand-alone virtual laboratory exercises for vibrations and control theory courses using Matlab Simscape. The virtual labs enable students to change the system parameters, develop a feel of the material, and record and observe the system response through mechanics explorer.

Keywords: Virtual laboratories, control theory, mechanical vibrations, MATLAB Simscape

1. INTRODUCTION

There is a growing interest in the visualization and application of fundamental engineering and science concepts to enhance student learning [1]. If the theory can be demonstrated either using a portable prototype or virtual laboratories, students not only comprehend the topic but also link it to its application areas. Although several virtual laboratories are available for gateway science courses, such as physics and chemistry, there is still a need for engineering courses [2]. Additionally, although laboratories are requisite in undergraduate engineering courses, the global crisis that arose with the COVID-19 crisis challenged student learning and made it difficult to achieve articulated course learning objectives correlated to the in-person laboratory or hands-on experiences.

Control theory is one of the major courses electrical, mechanical, computer and mechatronics and robotics engineering students are required to take for their graduation. Since control theory involves the use of scientific principles to solve real-world problems, it is essential that the theoretical concepts imparted to the students in a traditional classroom setting are supported by practical experience through hands-on experiments and/or virtual laboratories [3-7]. One salient but also the most challenging ABET outcome to achieve is that an engineering graduate should have the ability to solve a well-defined engineering problem by combining theory and practice [8]. Improving students' problem-solving skills is a requisite to educating new engineers who can meet today's challenges and become experts in their field of interest [9,10]. As the prior research shows, the hands-on experiences and lab components of engineering courses provide critical learning experiences for students to better understand the fundamental concepts [11-19]. However, many institutions have limited resources for laboratory equipment, and these limitations inhibit student learning due to the constraints on the use of available turnkey equipment. As a result, the lab components are often limited as the equipment is expensive, few in number, and bulky [20,21]. Moreover, labs associated with engineering courses are often offered in the following semester. Since students take the labs in the next semesters, many fail to remember the essential topics and lose interest in the subject matter. Also, while the simulation can be performed by the instructor in the classroom using limited commercially available software, some students find it difficult to fully comprehend, link, and visualize the physical movements associated with the fundamental phenomena [20]. Further, it is not always possible to demonstrate all the essential topics in a traditional course environment due to time constraints. Given that the laboratories are essential in engineering courses, the challenges for student learning that arose with the COVID-19 crisis and which we are still facing right now have made it much more difficult to achieve course learning objectives tied to the hands-on laboratory experiences.

Keeping engineering students' engagement and interest in a class throughout the semester is challenging. Students often lose their interest when they get overwhelmed with highly mathematical concepts. Students are taught the fundamental concepts of mechanical vibrations and control theory in a traditional manner where the instructor presents the topic and supports the material with class projects and homework assignments. The prior research shows that most students struggle to apply their knowledge to an engineering application in passive learning environments, hence missing the fundamentals and course learning objectives [22-24]. For instance, the highly mathematical nature of introductory level vibrations and control theory courses typically results in students struggling to understand the concepts [25]. In these classes, instructors need to provide interactive and constructive learning opportunities for students to better understand the fundamental concepts. However, with diminishing resources available to faculty, it is difficult to teach fundamental and abstract concepts. Although prior research on active learning has shown promising results in improving student learning, adopting learner-centered teaching in engineering courses requires a significant effort, such that the instructor can create in-class activities encouraging student participation and utilize technology to demonstrate or visualize abstract concepts. However, considering the engineering faculties' heavy workload and research requirements, faculty might not find adequate time and resources to create activities for their courses.

Also, as the COVID-19 pandemic has forced universities to shift to emergency remote instruction, digital learning tools have become a necessity, not just an accessory, to support students' engagement and learning. The prior research shows that virtual experiences complement the physical lab experience, and when virtual laboratories are coupled together with traditional courses and physical laboratories, it provides meaningful and fulfilling learning experiences that are greater than the sum of their parts [26]. Although virtual laboratories have the potential to provide an equal learning experience to the students and there are existing open-source virtual labs for K-12 and undergraduate science courses [27-29], there are very limited virtual labs for higher-level undergraduate engineering courses.

To address these challenges, we designed and developed open-source virtual laboratories for vibrations and control theory courses using Matlab Simscape in this study. The developed graphical user interface (GUI) application allows the user to change the parameters of the selected system such as its geometry, material properties, initial conditions, and the type of study (free or forces response). The students can run the simulations many times, work at their own pace and change the parameters of the system to observe the effect of the parameter on the system response, which is difficult to comprehend in a traditional learning environment and can work as a team for the assigned laboratory activities and projects.

The paper is organized as follows. Section 2 describes the developed modules, then section 3 discusses implementing the developed Apps into the courses or laboratories and states the targeted learning outcomes associated with each module. Section 4 discusses the assessment of student learning, and concluding remarks are provided in section 5.

2. MODULES OF THE MATLAB SIMSCAPE APPS

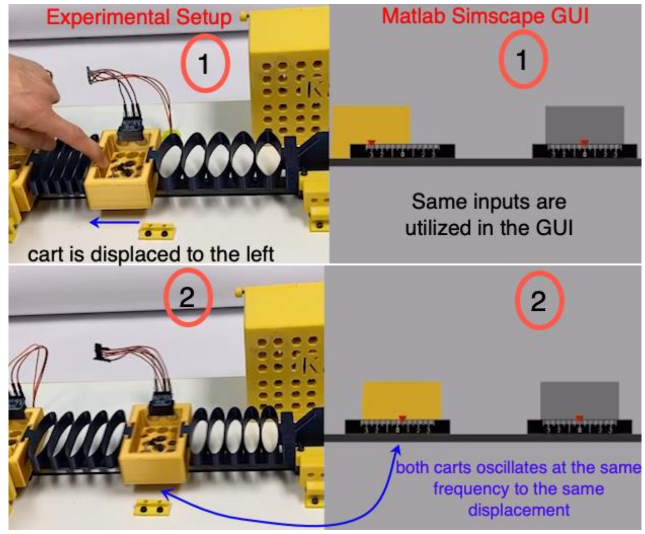

FIGURE 1: The procedure of validation of Simscape models

This section briefly discusses the submodules embedded in the virtual laboratories design in Matlab Simscape. Why Matlab? Matlab is frequently offered to first-year students in engineering programs in many institutions and as the simulation and programming software, Matlab includes various toolboxes such as Simulink, Simscape, system identification, and control design. One can design rigid and flexible systems in Simscape by either importing the cad model of the system or using blocks from the library and analyzing the response of the simulation while creating 3D visualization of the model through mechanics explorer. In order to determine how accurately the Simscape model simulates a mechanical system, we have tested the validity in our previous work [30]. In tandem, we created a translational 3D printed laboratory equipment, collected free response data simply by displacing the sliding cart, and released it while recording acceleration from the ADXL accelerometer and Arduino. Since the mechanical components required to model the mechanism are its mass, stiffness, and damping, we obtained the parameters using logarithmic decrement and theory and used the same parameters in our Simscape models to compare the results as illustrated in Fig. 1. Also, since the models are developed using the blocks from the library, the user doesn't need additional programs such as SolidWorks to be able to run the simulations.

2.1 Module 1: Modeling and Analysis of Rectilinear Vibratory Mechanisms

Since the introductory control course starts with modeling of mechanical systems concept, this module includes translational vibratory mechanisms to study the free and forced vibration of a single degree of freedom (SDOF) to 3 DOF translational systems as shown in Fig. 2. All the parameters and codes are embedded in the model and no additional data uploading is required for opening or running the simulations. Students need to select the system of interest by clicking on the title to be able to enter the parameters.

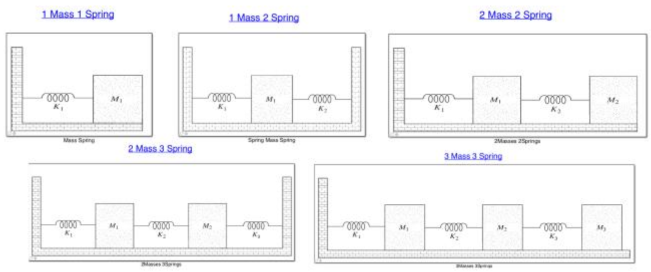

FIGURE 2: Models that could be analyzed in Module 1

Although the GUI only requires the user to enter the system parameters, if one is interested in creating a 4DOF vibratory mechanism with different combinations of springs using our template, then the user needs to click on the little arrow shown at the left bottom corner of each submodule to open the Simscape model as illustrated in Fig. 3. This would not only allow them to change the model completely but also enable them to export any data by adding a sensor similar to the provided template models.

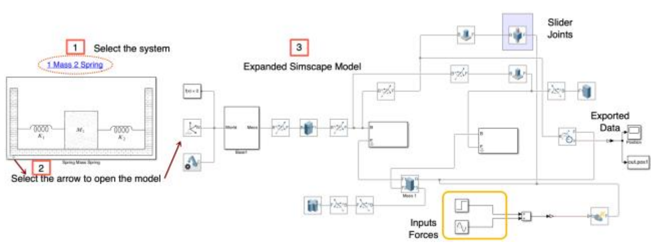

FIGURE 3: Simscape model of SDOF system with two springs

To study a system provided in this module, first, the student needs to select the title of the mechanism, and then double click to open the GUI. The mass, spring constants, and surface friction of all masses should be entered. Once the system parameters are set, either free or forced response boxes should be selected. The zero forces option in the free-response allows the user to disable the forces. In this case, the initial displacement of each cart can be selected using the slider or directly by writing the displacement in cm in the text box. Two forces are defined as input functions: step or sinusoidal. After unselecting the zero forces, and selecting the forced response, the amplitude value should be defined for step (a constant force), or amplitude and frequency are defined for harmonic input. The simulation time can be adjusted before simulating as the steps are depicted in Fig. 4. This action would open the mechanics explorer to visualize the motion in 3 dimensions. The positions of the carts are exported to the command window for further analysis. To give an example, students can plot the free vibration data, and also since the code to plot the power spectrum was already embedded in the model, they could simply plot the frequency response to obtain the natural frequencies of the selected 2 DOF system as shown in Fig. 5.

2.2 Module 2: Pendulum

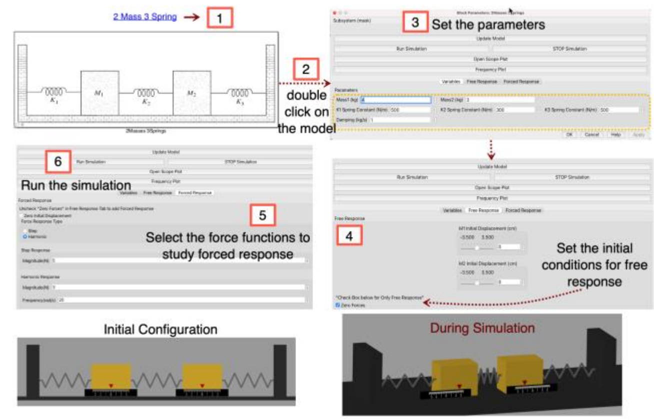

FIGURE 4: The steps need to be taken to run a simulation

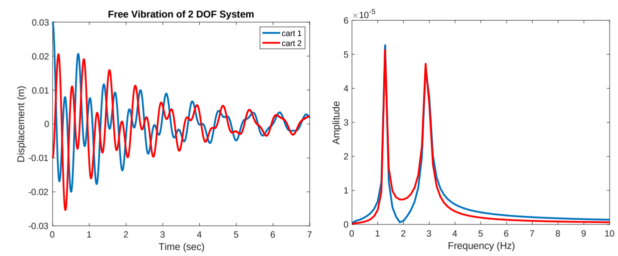

FIGURE 5: Free response and power spectrum of 2 DOF

The second module consists of the vibration analysis of the pendulum, control analysis of the pendulum, and analyzing the disturbance effect of the pendulum as shown in Fig. 6.

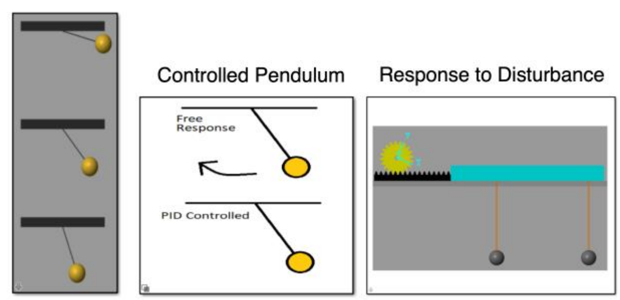

FIGURE 6: Module 2 consist of three submodules: free vibration of pendulum, control of pendulum and disturbance response of pendulum

With the first submodule, the student can study what would affect the frequency of oscillations of the pendulum by changing the length of the chord, tip load, and initial angular position of the three pendulums and plot the responses accordingly. Free and forced vibration analysis can be performed to study modeling, linearization, and system identification by selecting the title, double-clicking on the model, and entering system parameters similar to the previous GUI as depicted in Fig. 7. Students can have a quick observation through the scope or plot the response since the output data is shared in the workspace.

The second submodule focuses on the control design of the pendulum while comparing the controlled and uncontrolled

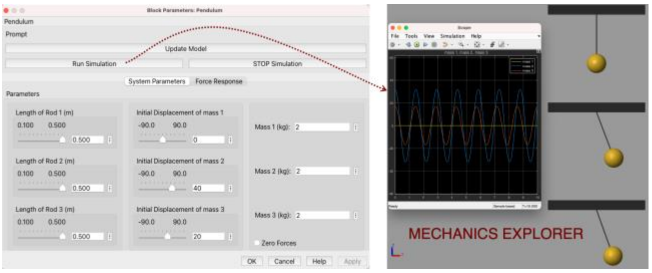

FIGURE 7: Free vibration of pendulum

system behavior. The input force is defined as impulse and the students enter the magnitude and the number of pulses of the input signal as well as the reference angle, so the pendulum stays at the same angle regardless of the disturbance constantly acting on the pendulum as seen in Fig. 8. The proportional, integral, and derivative (PID) controller coefficients can be obtained from the theory, designed by trial and error by adjusting the values or through the autotuning option embedded in the PID controller block in Matlab.

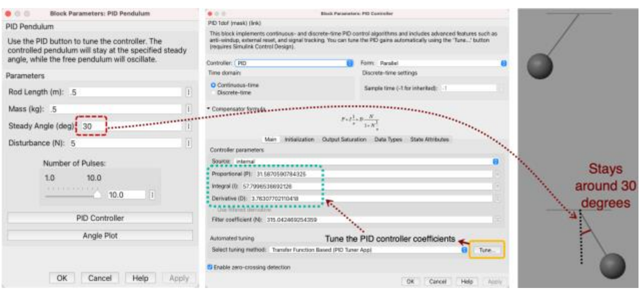

FIGURE 8: Controlled pendulum

Although the third submodule also considers the control of the pendulum, instead of selecting the impulse signal as the input, we designed a rack pinion instead for better visualization of the disturbance effect. Here, the length and tip load of the pendulum and the speed of the pinion are the inputs to the GUI. The submodule allows the students to adjust the PID controller coefficients. The goal is to maintain the pendulum angle at 0° while the force is applied via the rack pinion. The two identical controlled and uncontrolled pendulums attached to the same slider allow the students to understand how the controller changes the behavior of the motion as an example illustrated in Fig. 9.

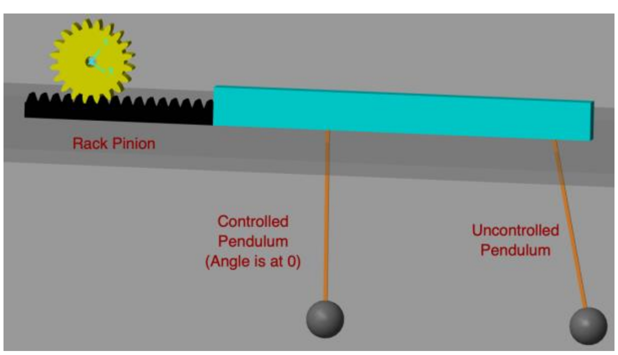

FIGURE 9: Controlled pendulum when the input is applied through a rack-pinion

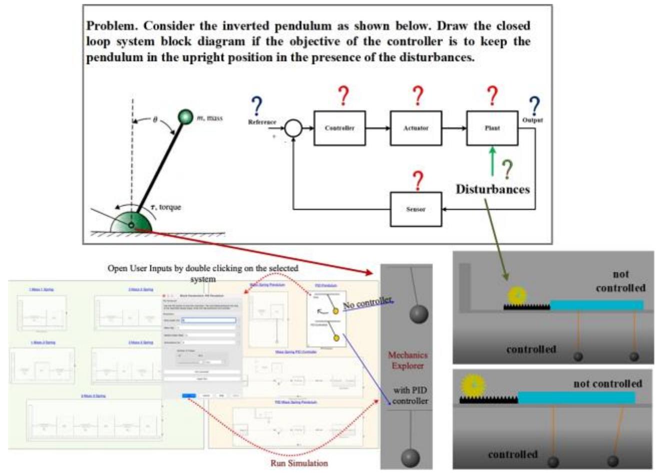

FIGURE 10: Example: Identifying parts of a controlled system

The problem shown in Fig. 10 is a classic example of an introductory level control theory course with learning objectives of defining a control system, describing its application areas, and basic features. The corresponding author has been teaching mechanical vibrations and control theory courses to mechanical engineering undergraduate students and has noticed that although students establish a good understanding of the design process, they struggle in identifying the system's parameters such as the actuator, controller, sensor, plant, desired variable, system output when a sketch is given without a written description of the problem. Using the App, an instructor can start a discussion with students to identify system parameters that students struggle with the most, then simulate the system using the App to emphasize the importance of the controller design by comparing the same system with and without the controller. Students also greatly benefit from a further discussion on the notion of disturbances with another simulation, such as the illustration of impulse or harmonic force loading on the pendulum-cart system through a rack-pinion design.

2.3 Module 3: Cantilever Beam with Ball

Module 3 presents the control of the ball position when it's dropped from a height onto the cantilever beam. A cantilever beam with a ball is a very common control application that's been extensively studied in the literature. Students can work on the derivation of the mathematical model by drawing the sketch and free body diagram, utilizing either Euler's laws of motion or the energy method, and compare the theoretical model with the simulation response obtained from the GUI App. In this module, students can change the altitude at the ball is dropped, select the desired position of the ball, and tune the controller coefficients until the ball reaches and stays at the desired position as shown in Fig. 11.

3. IMPLEMENTATION OF THE VIRTUAL LABS IN TEACHING AND LEARNING AND TARGETED OUTCOMES

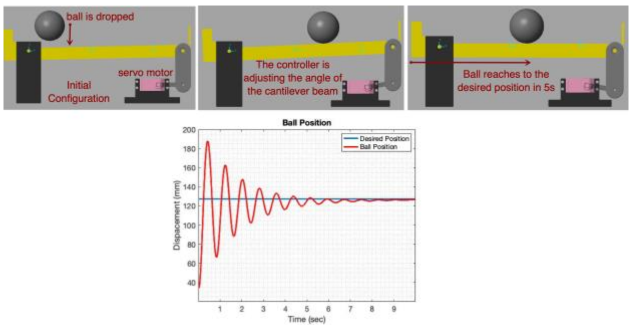

FIGURE 11: Control of ball with cantilever beam

In our previous work, we designed and developed low-cost, portable, and 3D printed laboratory equipment that is customized for vibrations and control theory courses so instructors can bring the equipment to the classroom and demonstrate the topic within 5-10 minutes [1,20,21,25]. However, in this study, we aim to visualize the vibrations and control theory concepts that are difficult to understand from theory alone. To address this issue, we developed an open-source and compact virtual App consists of 3 modules and doesn't require additional resources (see Fig. 12). If a user doesn't have a desktop version of Matlab R2021a, the GUI can be opened through Matlab Online. Once double clicked on the main GUI, it will open two new models: vibrations and control. Depending on the study, students can either select vibrations and work on the rectilinear system (1 DOF to 3 DOF with combinations of springs) and a pendulum or proceed with control models and design controllers for pendulum and cantilever beam with a ball. Although not mentioned in the previous section, trajectory control of a SOF mass-spring-damper system was also created.

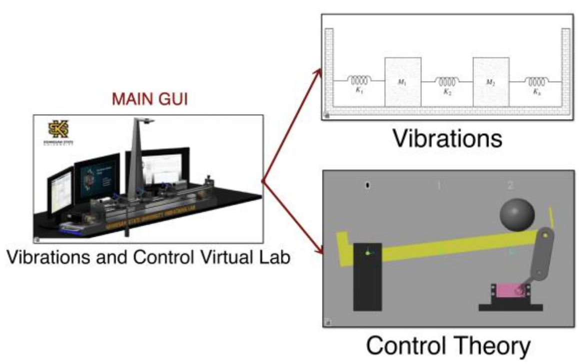

FIGURE 12: Developed GUI

The App can be implemented in face-to-face courses, laboratories, and online/hybrid courses in various ways. The instructor can demonstrate the concept using the App as a class activity after presenting the topic and further continue with discussion such as "Why" and "What would happen if I changed certain parameters?". The instructor can also assign homework or project. Students also can simulate systems following the instructions in the class either as a team or individually.

3.1 Mechanical Vibrations

The learning outcomes that can be achieved using the submodules in the vibrations App can be enumerated as but not limited to: (1) Derive the equation of motion of SDOF to 3 DOF translational and rotational systems, (2) Obtain the system response for different values of spring and damping constants, (3) Compute the natural frequency, damped frequency, damping ratio using the free time response and logarithmic decrement method, (4) Design a system in Matlab Simscape and simulate the system and analyze response in Matlab Simulink, (5) Calculate the vibration modes of multi degrees of freedom systems and set the initial values accordingly in the App to acquire natural frequencies from the power spectrum, (6) Design a vibration isolator, (7) Calculate the magnification factor, (8) Solve forced system response in Matlab, (9) Find the transfer function of the system, and (10) Solve damped and the undamped response of the system when subjected to input forces.

3.2 Control Theory

Introductory level control theory course deals with the modeling of mechanical, electrical, electromechanical systems, representing the equations of motion in the frequency domain (transfer functions) and time domain (state-space form), the response of first and second order systems to impulse and step inputs, stability, steady state errors, root locus, bode diagrams and PID controller design using root locus and Ziegler Nichols method. The general learning outcomes for the control App can be listed as (1) Design and analyze a control system, (2) Develop mathematical models of the physical systems and obtain transfer function models, (3) Use Ziegler Nichols method to design a PID controller for the trajectory control of SDOF translational system, (4) Model disturbances and (5) Perform stability analysis.

4. ASSESSING STUDENT LEARNING

A modified version of the Student Assessment of Learning Gains survey (or SALG) [21] has been developed to collect data on student perceptions of their learning. This modified SALG contains Likert-scale questions addressing how student learning is affected by the design of the laboratory module, how much the module impacted their development of engineering skills used in complete the laboratory, impact of the module on student understanding of key concepts, and student confidence in their ability to demonstrate each learning outcome as a result of completing the module. Finally, open-ended responses are solicited related to the pros and cons of learning with the module compared to other online laboratory formats.

The modified SALG was piloted for module 1 on rectilinear systems with 17 students. Results show the interactive nature of the module as rated by students as the most helpful aspect of the module design, rated as 5.82/6 with all students rating the interactivity as being of "much help" or "very much help". Among the engineering skills impacted by completing the module, students rated data collection within the Simscape context and ability to design a system to meet certain specifications most highly, with a mean score of 5.65/6 for each case. The ability to follow technical instructions had the least impact, at 4.88/6. Finally, student comments were nearly uniformly positive about their experience learning from an online laboratory module. They found it "eye-opening" that such a laboratory experience could be conducted online and indicated that the ability to play with system parameters and data was an added benefit over other online laboratory learning formats based on videos of experiments with associated data simply provided. However, some students did report challenges in accessing and applying certain MATLAB functions or difficulties in getting the simulation to run successfully on their computer.

The encouraging results of the pilot led us to re-deploy Module 1 as an application for designing a vibration isolator as described in the potential learning outcomes under section III.A. This exercise was incorporated in the Machine Dynamics and Vibrations course with 128 students across three sections. The questions we asked were equivalent to those in the pilot, except that new learning outcome statements were slightly modified to fit the new context, and the scale for achievement of learning outcomes was modified to provide greater variability in the results.

Despite learning remotely, students were allowed to work with peers on the assignment in small groups, similar to a laboratory context. However, students found working with peers (4.32/6) much less helpful than getting feedback directly from the instructor (5.31/6). Overall, ratings were lower than the pilot regarding the skills and knowledge students felt they gained from the exercise, with knowledge items receiving higher ratings that skills items. For example, ability to connect to real world applications and comprehension of the theoretical concepts were rated at 5.13/6 and 4.86/6, respectively, while solving problems and breaking down and analyzing problems were rated at 4.77/6 and 4.73/6, respectively.

Student ratings of their confidence with respect to achieving the learning outcomes from the lab ranged roughly equally between feeling they could teach it to someone else, do it on their own, or do it with some assistance. Ability to determine the natural frequency of a system and ability to visualize forced response in SDOF and 2SOF systems rated highest while deriving the equation of motion for a system rated lowest. However, difference in these results were slight.

Notably, our results illustrate that while students reported they made significant gains in understanding the theoretical concepts, they still did not feel confident in deriving equations. Therefore, further quantifying student understanding of the theory is needed. In addition to the SALG, data from student lab write-ups can be collected for analysis in the future to measure student performance on achievement of the learning outcomes for each module. These direct results can then be triangulated against the indirect data collected via the SALG.

5. CONCLUSION

In this paper, we presented an open-source virtual laboratory designed for undergraduate level mechanical vibrations and control theory courses in Matlab Simscape. Since the models created in Matlab Simscape visualizes the simulation in 3D, and many institutions have a membership to Matlab, once the developed App is downloaded, anyone can perform analysis by changing the parameters of the systems such as its mass, stiffness, and damping. The virtual App is comprised of two main modules: vibrations and control. The vibrations module consists of SDOF to 3-DOF translational systems and one control design for the SDOF mass-spring-cart model. The control module has the PID controller design practices for pendulum and cantilever beam with ball models.

Since the modules are designed to help students better understand the theoretical concept and provide faculty to demonstrate the concepts while teaching, more complex designs as case studies will be created in the future. Also, the virtual labs will be compiled as a stand-alone package and a web-based application that can run on a local computer or a remote server *without the need for licensed platforms* in the future.

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