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An interactive virtual laboratory for dynamics and control systems in an undergraduate mechanical engineering curriculum - a case study

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ABSTRACT: Providing engineering students with the necessary practical skills is essential. This is typically achieved through face-to-face delivery of several engineering laboratories. To avoid the shortcoming in students' skills attainment, several institutions have proposed indirect delivery of engineering laboratories through on-line simulations or interactive platforms. The use of remote virtual laboratories has been widely recognised for the past decade as a complimentary tool in the constantly evolving world of modern engineering. Delivering mechanical engineering laboratories has become more challenging in different important areas, such as manufacturing, dynamics, control and others. In this article, the authors articulate the use of interactive virtual laboratories as a teaching method of dynamics and control systems laboratory. The interactive virtual laboratories are delivered remotely to junior year mechanical engineering students during the lockdown of university facilities. The use of the interactive mechanical engineering laboratories has ensured the attainment of learning outcomes associated with the delivery of dynamics and control systems laboratory.

Keywords: Distance learning, virtual laboratory, dynamics, control systems, interactive experiments

INTRODUCTION

Engineering laboratories are the foundation of most engineering education principles and practices; commonly, engineering disciplines incorporate practical laboratory in their curricula. It is well-established that the gained hands-on laboratory experience has a significant role in preparing engineering graduates to perform well in leading the current industrial revolution and recent technological innovations. With the constant evolution of scientific and technological advances in the modern world, the need to continuously change engineering curricula for the better has become a regular procedure for most renowned educational institutions [1]. This will facilitate designing on-line classroom-based simulations for manufacturing processes courses [2].

According to Campos et al, simulation-based education allows students to learn complicated concepts better and make them feel more involved in practical learning [3]. The interest in using simulations as teaching tools is rising as course instructors are seeing them as a potential way to help students gain more hands-on experience and make them more familiar with how tasks are done in the real world. Due to the rapid technological developments, computer simulation capabilities are getting larger and more ambitious than ever, and simulation games and software have shown their effectiveness in teaching engineering students as it allowed them to improve their critical thinking, decision making and many other cognitive skills.

A simulation is a representation of the real world and the closer the simulated world is to reality, the better the learning experience. For example, students can learn about supply chain management and logistics through simulation software, which can help them gain lots of hands-on experience and be better prepared for a job in that field once they graduate. The use of innovative technologies and computer-aided approaches in teaching engineering students is currently a necessity, as laboratories are not as accessible as before [4].

According to Hauge and Riedel serious games can help students learn hard and soft skills; this will improve students' capabilities in taking decisions in the real-world situations similar to experienced conditions in the simulated game [5]. The Beware game starts by putting students in a simulated world in which they work for a production company, and play roles in the field of procurement, manufacturing and services. They are required to work together and evaluate risks to succeed. Any lack of co-operation by the students that could result in poor information exchange and wrong decisions will lead to negative consequences that are like the consequences that happen in the real world. The game then introduces an inter-organisational network to the work environment, and things become more complicated and more difficult as co-operation and risks assessment become more crucial [5].

COMPUTER SIMULATIONS AS A TEACHING TOOL DURING PANDEMIC TIMES

The Covid-19 pandemic has brought lots of challenges to the education sector since the whole sector was forced to transform to the on-line learning model and stop the classic face-to-face learning model. Engineering laboratories are commonly based on face-to-face interaction between the student and the instructor to learn practical skills according to engineering standards. Therefore, institutions had to bring new models and ways to make sure the learning experience is as much as possible interactive and exciting for the students even in the absence of face-to-face learning.

According to Moorhouse, one of the main challenges in on-line teaching is the lack of proper communication between the student and the instructor [6]. Students also found it difficult to communicate with their course instructor, and they were not as much communicative with the instructor as they used to be when the course was being taught face-to-face. However, course instructors were able to develop new and more effective teaching strategies that make on-line learning more interesting as the transition to on-line learning was inevitable due to Covid-19.

The digitalisation of laboratory education is a complicated task, and for the success of on-line learning proper transition to technological means of education is important. Learning techniques, tools, means of delivery, should be positioned in a virtual zone and offered with all types of innovation opportunities. A recent route to investigate the innovation required to confront rising training needs that emerge from challenging circumstances has been outlined by Nuere and de Miguel [7].

Essential aspects of the learning process depend on factors, such as accessibility, learning models and teaching models. In various theories related to distance learning, it has been established that the student is the main component in any educational system. The instructor is an additional important component and, ultimately, the assets accessible to facilitate the learning model and provide enough technological advancement are also another important factor [7].

Due to the unexpected Covid-19 pandemic, everything had to happen quickly. Many instructors are encountering difficulties, such as lack of experience in using on-line teaching tools or lack of assistance from educational technology groups. Besides the difficulties that the faculty are facing, students are also suffering because of the inability to adapt to the new on-line learning as they lack appropriate learning resources or decent learning conditions when they are at home.

Bao suggests some instructional methods to enhance students learning focus, as well as participation to accomplish an effortless shift to on-line education [8]. Universities have recognised that making emergency plans is essential for unexpected circumstances, as in the Covid-19 pandemic, when suddenly, all courses and laboratories had to be changed to the on-line learning model. Such plans will guarantee that learners focus on on-line learning, while course and laboratory instructors sensibly transfer the material of the in-class learning into various subjects and implement a flexible teaching technique. In laboratory delivery, teaching assistants and laboratory instructors are a crucial part of enhancing the on-line learning experience, as they can help others with the technical prerequisites of virtual teaching [8].

INTERACTIVE VIRTUAL LABORATORY DURING REMOTE LEARNING

The delivery of engineering laboratories remotely was the most challenging aspect of on-line learning during the current pandemic. While it is very important to maintain the hands-on experience gained during the face-to-face delivery of engineering laboratories, the learning outcomes of laboratory courses can be partially or fully attained using well-designed interactive laboratory experiments in remote learning. Several institutions have proposed different interactive learning experience for engineering laboratories that are involved in their curriculum.

A virtual laboratory application is showcased through a virtual experiment by Shah et al [9]. The authors describe the features of the application, its ease of use and integration with current study plans; furthermore, the student benefits from automated supervision and guidance throughout the virtual laboratory.

Another study aims to identify the criteria that make virtual laboratories effective for both engineering students and instructors [10]. The students benefited from the availability of components, the ability to set their specifications and automated graph plotting, while instructors found that the laboratories help in avoiding plagiarism and having a semi-automatic assessment [10]. Other authors describe the results of involving students in a virtual pre-laboratory practice session and its effect on the students' learning gain. Statistical methods were utilised to show that virtual pre-laboratories did in fact enhance the students' learning gain. Out of eight demographics, the results showed that only high school GPA and *transfer status* affected the learning outcome [11].

A recent study describes an assessment of the transition from a physical laboratory to a virtual laboratory in an engineering course. Feedback was received from students before and after the transition; the students' performance in the virtual laboratory was *comparable* to the one in the physical laboratory; however, the students found that learning virtually was more challenging and less immersive [12]. In a recent paper, Singh et al developed a VR-based learning environment and studied its effectiveness on students' knowledge development, cognition and motivation [13]. The results show a positive impact in all three aspects, an enhanced understanding of the laboratory equipment and less worry regarding the malfunction of the hardware [13]. Ahuja et al carried out statistically studies on the effect of advanced VLSI virtual laboratory on students' understanding. Pre- and post-tests and a feedback survey were conducted, where the results revealed a positive impact on students' learning and understanding of the laboratory [14].

A Web-based hybrid laboratory that can combine the simulation with real data is presented Luo and Chhabda [15]. The results of a pilot study showed that students still preferred a traditional laboratory experience, mostly for the appeal of hands-on experience. However, the grades of the students using a virtual laboratory are comparable to the ones using a physical laboratory. In a recent review, Gamage et al studied methods utilised by universities during the Covid-19 pandemic [16]. The authors discuss the technology required (particularly for virtual laboratories) for such a transition; they also urge teachers to change their approaches and point out that the first problem to be solved is providing the Internet to the entire globe, since all these transitional methods rely heavily on its availability [16].

A Web-based platform named RVL@DEI-UC allows the user to conduct experiments remotely and acts as part of an intelligent tutoring system. The study by Cardoso et al shows its integration and potential in engineering courses at an early stage of the system's development [17]. A recent paper depicts the use of on-line learning activities, virtual laboratories and comprehensive e-learning environments in scientific subjects [18]. The results show that such methods served both students and instructors positively, as students developed a conceptual understanding of the topic, and instructors were able to overcome the lack of time and resources they usually have to face [18].

In another recent study, Jukkala et al illustrate the use of a virtual laboratory and discuss its helpfulness in engineering courses. The results show that combining both virtual and physical learning gives the best results for students. Virtual laboratories are easy to use and help students avoid common blunders [19]. Rico at al portray the early results of a virtual laboratory environment created with an open-source software [20]. This software shows promise as it is delivering an easy way to use the virtual laboratory that is inexpensive and does not require programming skills to set up which eases its integration.

Ouyang et al presented a prediction method of the popularity of on-line videos and their future view count. The results are validated with a large dataset, where the suggested method gave promising results with a significant drop in errors in comparison to two other state-of-the-art methods [21]. A recent paper by Trentsios et al aims to combine virtual reality (VR) and traditional 2D visualisation of a remote laboratory by creating precise frontends that can be utilised through VR and virtual laboratories. The researchers were able to produce an application useable with a VR system or a desktop. The model shows promise, even at its earliest stage [22]. A review of the existing virtual laboratory simulations and remote laboratories and their limitations is carried out by Balamuralithara and Woods [23]. The review shows that on-line laboratories have potential as a strong alternative to physical laboratories with multiple advantages to students; however, the technology is limited and can be improved by implementing 3D and a GUI.

CASE STUDY: ON-LINE INTERACTIVE DYNAMICS AND CONTROL SYSTEMS LABORATORY IN ABU DHABI UNIVERSITY

At Abu Dhabi University, dynamics and control systems laboratory is a junior level course in the mechanical engineering curriculum offered in the spring term. The laboratory is commonly practical and involve several hands-on experiments that students perform over regular semesters. The laboratory has two pre-requisites: dynamics and control systems. Regularly, except for the current lockdown, the laboratory aims to provide students with a full understanding and detailed hands-on skills of dynamic systems analysis and control implementation. Students are usually engaged in projects that incorporate the three main areas of mechanical engineering, thermo- fluid, dynamics and design. For each project, students select a process, model it, simulate it, design a controller for it and implement the final control system.

The students use components from a large assortment of dynamic systems and mechatronics components provided in the laboratory. The course also aims to familiarise students with entrepreneurial opportunities related to mechatronics, dynamics and control, as well as to increase their commitment to ethical practices, and to social and environmental issues relevant to mechatronics, dynamics and control.

The laboratory complies with the ABET criteria for student outcomes:

1. Utilise principles of multi-variable calculus, differential equations and linear algebra to solve mechanical engineering problems.
2. Apply principles of physics and chemistry to solve mechanical engineering problems.
3. Conduct experiments and data acquisition.
4. Analyse, interpret and present data.
5. Write effective technical reports.
6. Use of modern engineering software to aid in solving practical problems.
7. Use of modern equipment to aid in solving practical problems.

Different virtual interactive experiments have been designed for this laboratory using Python as a programming language. The laboratory experiments include different variables assessment, modelling and control. The implemented graphical user interface is easy to use by students and allows them to perform different control schemes to verify the effect of parameters used.

EXPERIMENT 1: WATER LEVEL CONTROL USING A PID CONTROLLER

In this virtual laboratory, students can investigate the effect of the PID on the response of the system. Initially, students will vary the gain of the P controller, while keeping the other controllers set to zero. For every case, the *extract* button is pressed to extract the response graph, and the effect of increasing the P controller on the stability is investigated. The P controller is then set to zero, and the I controller is tuned to show the ability of the I controller to achieve zero steady-state error. The experiment is then followed by using a combined PI controller showing how it can provide a more robust response. The effect of the D controller on reducing the overshoot of the system is also investigated. The GUI of water level control using the PID controller is shown in Figure 1.

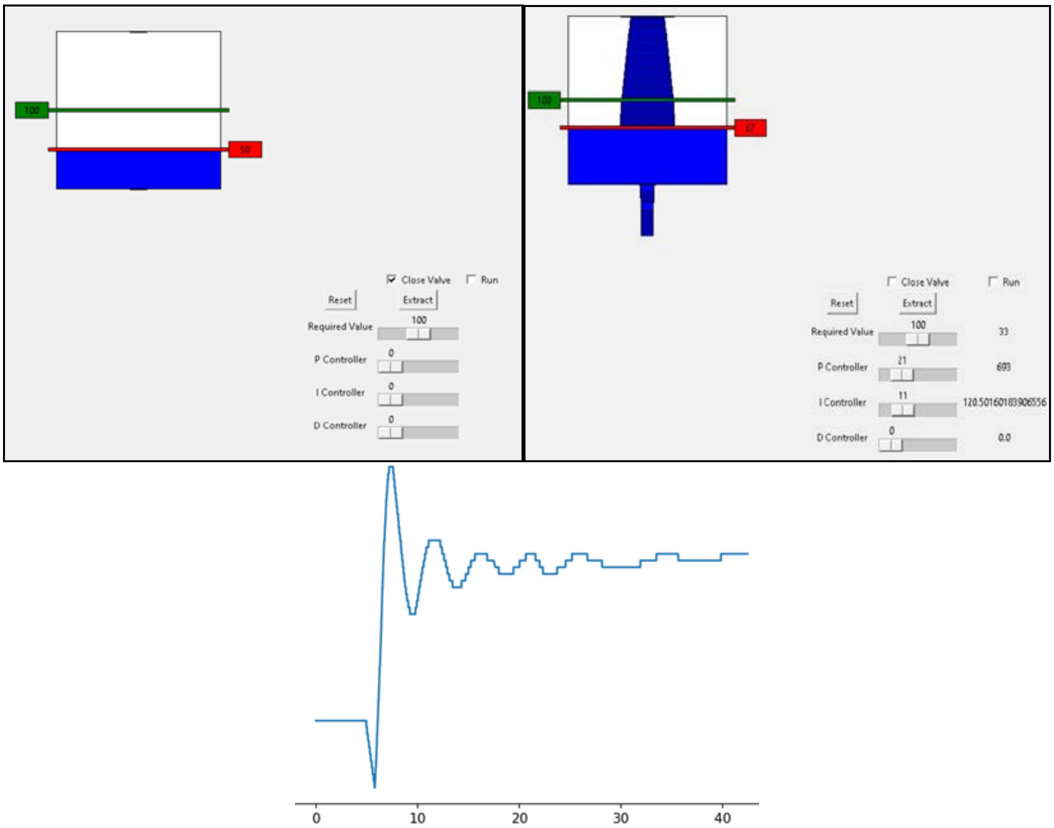

Figure 1: GUI of water level control using the PID controller with resulting level output.

Students will find the set of gains to obtain the optimal response. To the right of every slider, the output of the controller is shown to help students understand the signal sent to the plant. In the laboratory report, students are asked to include all the graphs and discuss the effect of every controller on the rise time, settling time, steady-state error and percentage overshoot. For certain selected graphs, students should calculate the rise time, 5% settling time, percentage overshoot and the steady-state error.

The drainage valve can be opened to represent the introduction of disturbance to the system. The disturbance due to the drainage valve is dependent on the level of water. Students are asked to change the set point and show the difference in the response. After all the above analysis, a tabulated response is provided along with the gains of a controller, and students are asked to find the output of each part of the controller, as well as the overall output of the controller at every timestep.

EXPERIMENT 2: STATIC AND DYNAMIC BALANCING

Dynamic balancing is a section in the Kinematics and Dynamics of Machinery course. The balancing techniques in the course are limited to rotating machinery rather than reciprocating machines. The dynamic balancing experiment is based on a simulator and a simple numerical solver. The simulator represents a shaft with four blocks, and the position of the block along the shaft, as well as its angular position, can be adjusted. The shaft can be tested for static and dynamic balancing.

The simulator allows for manually rotating the shaft showing students the ability of a statically balanced shaft to hold at any position it is kept at. Students will be given four positions/angular positions of the blocks, and will be asked to find the other four positions/angular positions of the blocks. The order of blocks is also specified leading to a bounded problem. Students should derive both the force equilibrium equations representing the static balancing, as well as the moment equations to allow for dynamic balancing.

In order to find the four unknowns, students are asked to use the numerical solver, which requires the user to input an initial guess. After every static or dynamic test, the degree of unbalance is shown numerically, as well as through the intensity of the vibration of the shaft. The non-zero values shown for a balanced shaft prove that all systems will have a degree of unbalance in real life, which should be kept to a minimal value to extend the life of the machine.

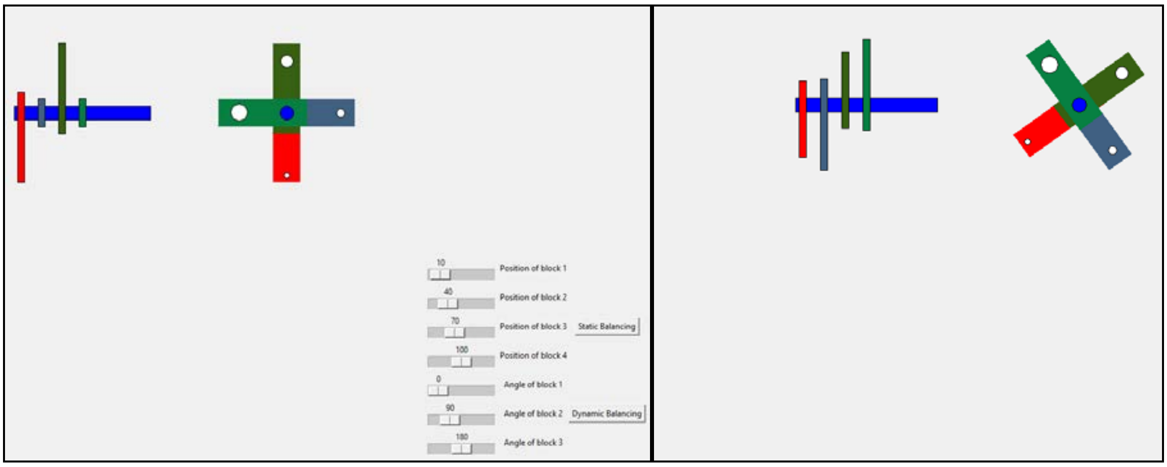

Figure 2: Static and dynamic balancing with different parameter selection.

EXPERIMENT 3: CAM AND FOLLOWER

Figure 3 shows a cam and follower assembly. Three different cams are available; namely, constant speed, constant acceleration and higher order polynomial. Even though the first two cams are not practical, they were added to the simulator in order to show students why such cams lead to infinite spikes of force or vibration. The size of the cam can be changed.

The simulator allows students to generate the profile of the cam as an Excel sheet, where students can continue the cam analysis finding the speed and acceleration by numerically differentiating the profile. The graphs obtained are position, velocity and acceleration of the follower against the angular position, and the angular velocity is given, so that students can evaluate the quantities against time. Students are asked to give real-life applications for cams, as well as discuss the various types of followers that can be used.

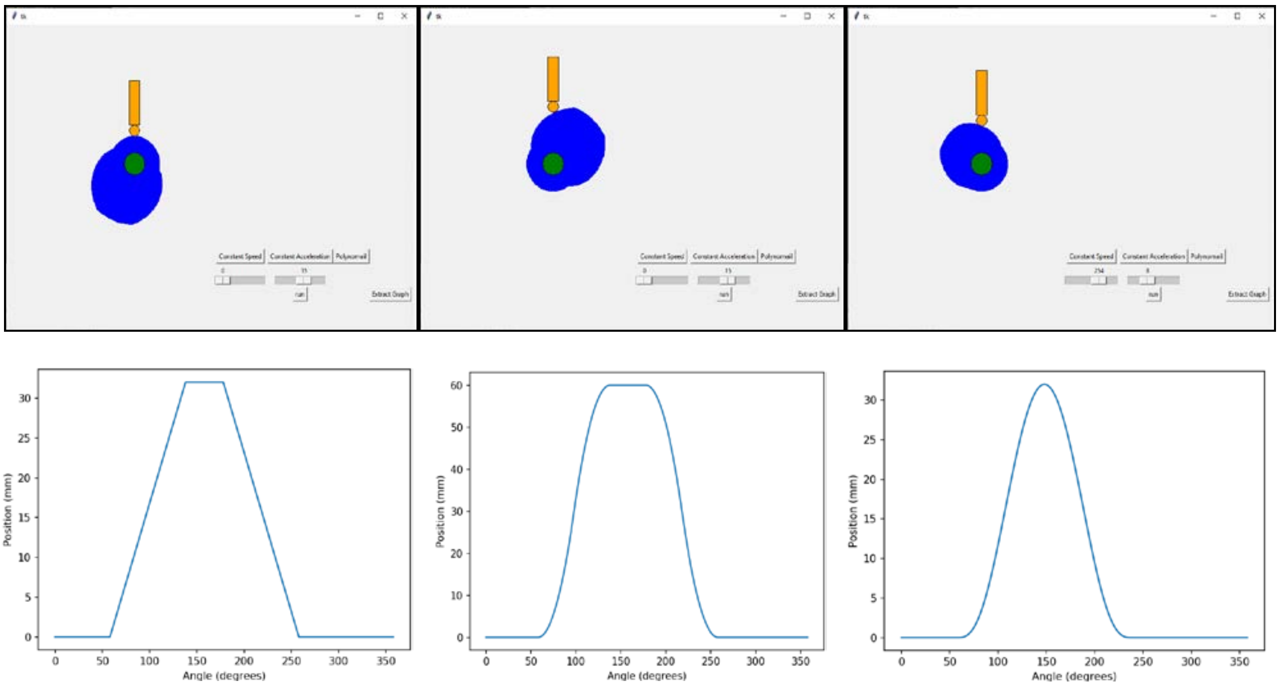

Figure 3: Cam and follower animation with selected displacement diagrams.

Students' feedback and assessments showed a satisfactory level of learning outcomes assessment. Although students have expressed their interest in hands-on laboratories, they also demonstrated interest in developing interactive and virtual learning environments.

CONCLUSIONS

Engineering education is currently facing several challenges to deliver the required practical experience necessary to attain engineering skills associated with engineering laboratories. To bridge this gap and enhance the attainment of dynamics and control laboratory learning outcomes, this study proposes the use of custom-made interactive and virtual laboratory to deliver a dynamics and control laboratory course.

In this study, students were able to achieve the expected learning outcomes of the laboratory through performing multiple tests on process and control parameters and constraints. The students' feedback showed adequate satisfaction with learning when using an interactive laboratory in studying dynamics and control systems.

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BIOGRAPHIES

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