Implementation of a Virtual Mechanics Laboratory for a first year undergraduate engineering subject using MATLAB App Designer

Huey Yee Chan
The University of Melbourne

Corresponding Author Email: huey.chan@unimelb.edu.au

ABSTRACT

CONTEXT

In wake of the COVID-19 situation in 2020, when universities were faced with the transition from face-to-face learning to online delivery, many educators found themselves tasked with having to convert previously classroom-based teaching material to an equivalent online adaption. The transition was particularly challenging in a first-year engineering subject where hands-on laboratory experiments play an important part in the learning of basic mechanics principles as a foundation in engineering. Adaptation of physical hands-on experiments into the form of interactive virtual simulations was necessary to ensure students had an equally comprehensive laboratory experience in the online delivery mode.

PURPOSE

This paper describes the development and implementation of a virtual laboratory for a set of mechanics experiments as an alternative to the physical hands-on laboratory. The interactive simulation application replicates the procedures of a physical mass-spring system investigation that applies two fundamental mechanics concepts, resultant forces and principle of moments.

APPROACH

The virtual laboratory application is a user-friendly graphical user interface (GUI) integrated with a program code that models a physical spring system, developed in MATLAB App Designer. Key features of the application include animated outputs and virtual measurement tools that emulates the procedures of the actual experiment and MATLAB modelling that takes into account inconsistencies that may arise in real measurements. For deployment purposes, the simulation program in App Designer was compiled into a standalone executable and run using the MATLAB runtime environment.

OUTCOMES

The virtual laboratory activity was successfully conducted during the online workshop classes in the first-year engineering subject at the University of Melbourne across a cohort of over 600 students. The simulation application in the virtual setting achieved similar learning outcomes as the experiments in the physical setting, but the activity was completed in significantly shorter times as compared to the expected physical hands-on.

CONCLUSIONS AND RECOMMENDATIONS

The virtual experiments offered efficiencies over physical experiments in terms of minimising experimental procedure delays and allowing more focus on concepts and theories but unavoidably compromising other hands-on experience such as equipment set-up, calibration, real-world experimental observation, and troubleshooting. For a more comprehensive virtual laboratory experience, future work to model the virtual environment more accurately to represent real world behaviour is recommended.

KEYWORDS

Virtual laboratory, MATLAB App Designer, simulation application.

Introduction

In April 2020, when movement restrictions came into effect during the COVID-19 pandemic in Victoria, Australia, the majority of courses offered by the University of Melbourne were forced to transition from face-to-face learning to online delivery at short notice. Educators suddenly found themselves faced with the challenging task of having to convert previously classroom-based teaching material to an equivalent online adaption within a limited time frame. Whilst lectures could be offered online in the form of recorded or streamed videos, hands-on laboratory experience was more difficult to transition over. The transition was particularly challenging in a first-year engineering subject where hands-on laboratory experiments play an important part in the learning of basic mechanics principles as a foundation in engineering. This paper documents the adaptation of three physical hands-on experiments in a first year engineering subject into virtual laboratory experiments, with the aim to provide students an equally comprehensive laboratory experience in the online delivery mode.

Within the process of transitioning to online delivery mode, various forms of virtual laboratory substitutes were considered, including video pre-recordings of the laboratory experiments where students observe experimental procedures and record measurements and data from it. Laboratory video recordings have thus far been shown to be effective as pre-laboratory preparation, for example in studies by Schmidt-McCormack,et al. (2017) and Rodgers, et al. (2020), but not so much about their use as a complete substitute for physical laboratories. For the author's primary purpose of transitioning hands-on laboratory to a virtual equivalent, an interactive simulation application that replicates the actual experimental process was favoured over video pre-recordings.

The inspiration behind the development of the interactive simulation application stemmed from the commercially available Physics Education Technology (PhET) Interactive Simulations project (PhET Interactive Simulations, 2020). Although simulations available within the PhET collection could be used to demonstrate the engineering principles of interest, they were insufficient to replicate the existing physical laboratory experiments that had to be transitioned online. This shortfall led to the author's development of a suite of experiments within a custom simulation application that has been specially designed to meet the needs of the university's first year engineering subject in demonstrating specific mechanics principles.

The simulation application was set up to allow students to essentially perform the experiment procedures as they would in the actual physical version. MATLAB App Designer, a graphical user interface development environment (Mathworks, 2020) was the tool chosen for the development of the application.

Modelling and Analysis

The basic mechanics principles of resultant force and moments are covered as part of the context in a first-year engineering subject at the University of Melbourne. To enhance the theoretical learning of these concepts, students perform a laboratory experiment applying knowledge of spring force, resultant force and the principle of moments to estimate the weight of an object.

To provide some perspective on the laboratory activities in the original classroom setting, students perform a suite of three experiments, first the Hooke's Law experiment followed by two experiments using a set of custom designed wooden spring scales.

In the Hooke's Law study, students perform the standard experimental procedures to determine the characteristics of a simple spring from the force versus extension graph governed by the linear spring equation below (Loyd, 2008),

$$F = kx + c \tag{1}$$

where F is the applied force, x is the spring extension with the applied force, k is the slope of the graph, that represents the spring constant, and c is the y-intersect of the graph.

Following that, the spring is placed on one end of a wooden balancing scale that acts like a see-saw to balance the combined weights of an unknown weighted object (a container filled with sand) and known brass weights, as shown in the layouts (a) and (b) in Figure 1. The two configurations of spring placement in two separate experiments will apply different mechanics principles, namely:

(a) equating resultant forces – spring and weights placed at opposite ends at an equal distance (of 19 cm) from the centre of balancing scale.
(b) a combination of resolving forces and equating moments – spring attached with an inclination at a distance of 29 cm from the centre of the balancing scale while the weights remain at 19 cm.

Note that the unknown weights for spring scales configurations (a) and (b) will be different as they are two separate experiments.
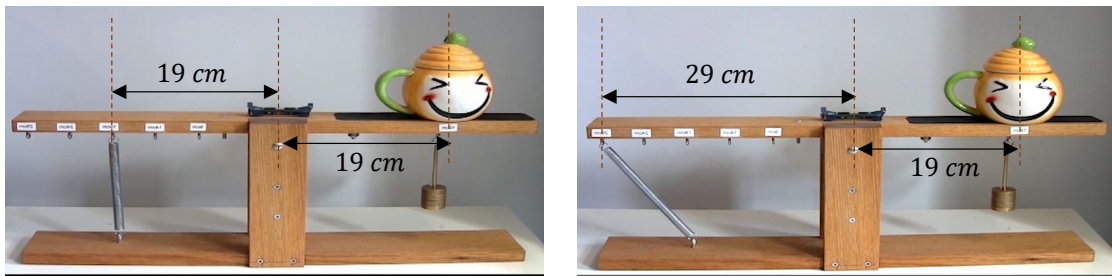
(a)   (b)
Figure 1: Two configurations of the Spring Scales experimental set-up

To illustrate the mechanics principles behind the spring scales experiments, the following section will derive the governing equations of the two spring configurations based on the virtual simulation application, which is modelled after the actual physical laboratory set-up.

In the virtual set-up for configuration (a) as shown in Figure 2, with the scales in the balanced position, the spring force on one end balances the weight of the unknown object and the known (brass) weights on the opposite end, resulting in the equation

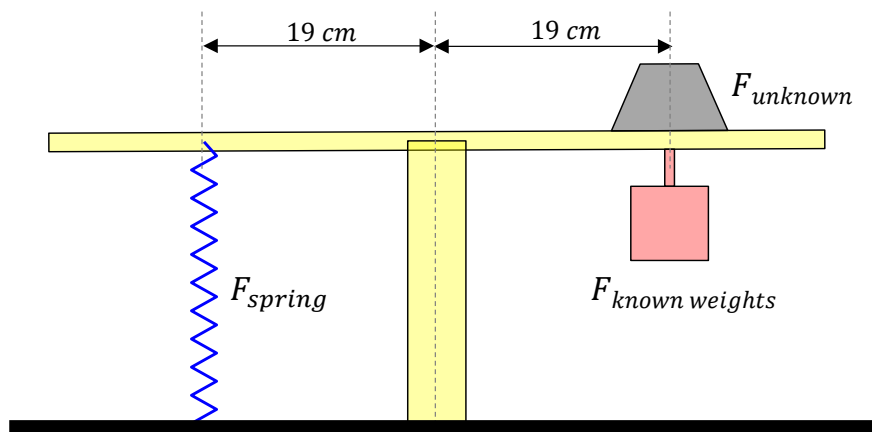$$F_{spring} = F_{unknown} + F_{known\,weights} \qquad (2)$$

Figure 2: Virtual laboratory set-up for spring configuration (a)

For spring configuration (b) as shown in Figure 3, with the introduction of spring inclination and a distance factor, applying the slightly more complex principle of equating clockwise moments to counter-clockwise moments along with resolution of forces results in the following equation when the scale is balanced,

$$F_{spring} sin\theta \times 0.29 = (F_{unknown} + F_{known\ weights}) \times 0.19 \qquad (3)$$

where θ is the measured angle between the spring axis and the horizontal platform of the spring scales.
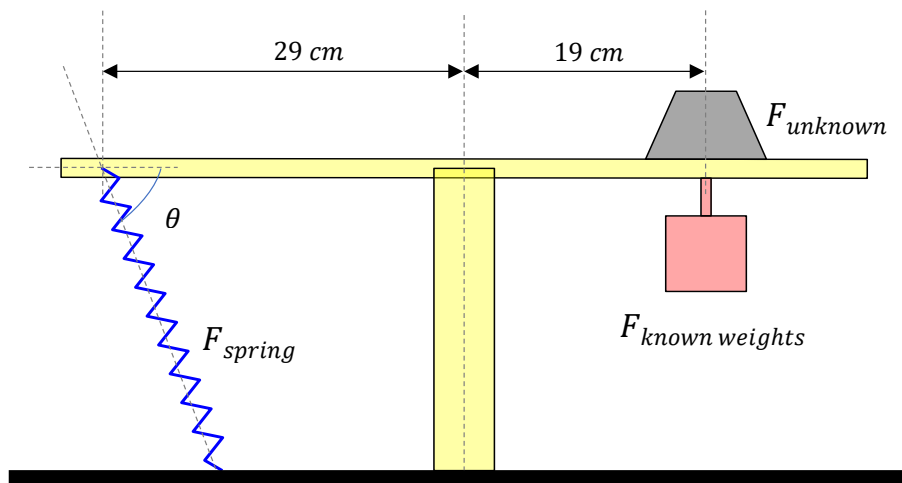

Figure 3: Virtual laboratory set-up for spring configuration (b)

The known spring characteristics from the Hooke's Law experiment, the known brass weights added to balance the spring scales and other measured parameters such as distance and spring angle allow the unknown object's weight to be calculated from the governing equations.

Design Considerations

The main intention behind the development of the virtual laboratory was to provide an environment where students can experience a virtual equivalent of the practical procedures of the physical laboratory, covering 3 key elements, experimental execution, measurement methods and real world non-ideal behaviours. In the virtual laboratory application, these considerations were realised through an interactive graphical user interface (GUI) front that combined animated response sequences with virtual measurement tools and background system modelling that incorporated random fluctuations to take into account inconsistencies that may arise in real measurements.

An important aspect of the virtual laboratory that the author took special care in designing was the user interface in accordance to recommended usability requirements (Cooper, 2005). According to Cooper, the user interface needs to enable the student to carry out all the tasks and make all the observations that are necessary to achieve the learning objectives of the experiment. It is important that students focus on performing the activity rather than on the use of the software. For this reason, the virtual laboratory interface was designed using mainly click buttons and drop-down menus to offer simple and straightforward operation.

Final considerations for the virtual laboratory were the scalability and the accessibility aspects of the application, for deployment to a large cohort of over 600 students within the subject. The way a remote experiment is designed will govern its accessibility to nearly all users irrespective of any disability (Cooper, 2005). For this reason, a stand-one executable application was

deemed the best option as all students are provided access to the university's remote desktop server that contains the necessary software to run MATLAB executable files.

Software Description

The layout of the virtual laboratory's GUI was created using the set of interactive user interface (UI) components available in MATLAB App Designer (version R2019b). The GUI development environment allowed the integration of mathematical models that governed the behaviour of the spring and balance scales systems developed in MATLAB code for control of the simulation.

The default interface upon loading the virtual laboratory application is the Hooke's Law Experiment tab, as shown in Figure 4. In the experiment, users are provided with a selection of 6 mass values in a dropdown menu to load the spring with.
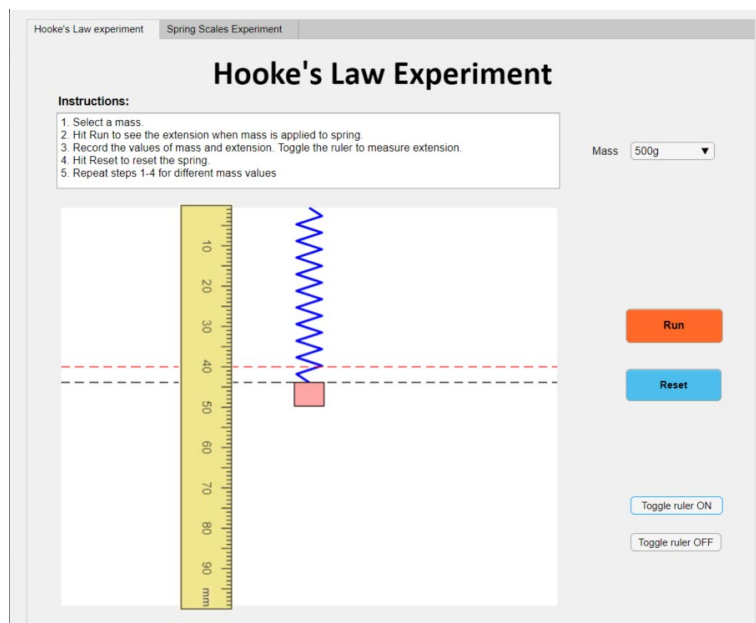

Figure 4: Hooke's Law Experiment tab

Whenever the user clicks on the Run button in the GUI, a background MATLAB function is invoked to process the applied mass and perform the necessary calculations to produce the appropriate animated spring extension response. The MATLAB code modelling the animated spring behaviour was adapted from Morales's spring algorithm to plot and animate a 2D-spring (Morales, 2020), consistent with the linear spring behaviour described in equation (1) to generate the value of spring extension for each respective applied mass. A random noise factor of between 0.8 and 0.9 was introduced into the c value of the equation to generate non-ideal behaviour in the linear spring, as a way of incorporating real-world measurement inconsistencies, shown in the equation below.

$$x = \frac{F - (c \times random\ factor)}{k} \tag{4}$$

A virtual ruler that toggles ON and OFF then allows for the measurement of spring extension, x, when the respective load, F, is applied. The set of 6 measurements of F and x from the GUI is used to plot a best fit linear force versus extension, $F - x$, graph to estimate the spring characteristics, k and c, as described in equation (1). To provide some variant within the experiment, 4 different springs were programmed into the simulation, of which one will be

randomly loaded each time the application is run. The spring characteristics, k and c, obtained here will subsequently be used to calculate the spring force, F_{spring} in the spring scales experiments.

Following the completion of the Hooke's Law experiment, a second tab within the virtual laboratory application provides the interface to the spring scales experiments as shown in Figure 5. For each of the spring configurations (a) and (b) respectively, users choose one of three different objects of unknown weight to measure. Additional known mass values to balance the scale are provided in a dropdown menu. When the user clicks the Run button, the animated spring scales will tilt at an angle controlled by the magnitude of the forces applied at opposite ends of the scale platform. In order to achieve balance, loading at both ends must be equal, and this is visually indicated by the red gauge needle pointing at the centre position.

For configuration (a), a ruler that toggles ON and OFF is provided for the measurement of the extension of the stretched spring when the scale is balanced, whose value when applied to the calculation of F_{spring} in Equation (2), will yield the value of the unknown weight. Whereas for configuration (b), two toggle ON/OFF measurement tools, a ruler and protractor for measurement of the spring extension and inclination angle, θ, respectively, are necessary for the calculation of the unknown weight according to Equation (3).
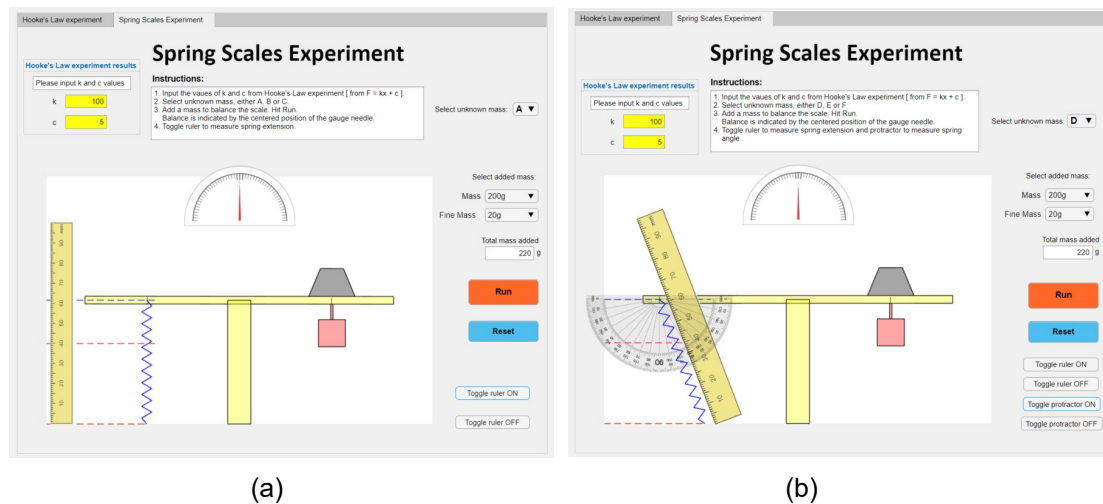

(a)   (b)

Figure 5: Spring Scales Experiment tab

For deployment to students, the application source code in App Designer was compiled with the MATLAB Application Compiler into a standalone executable and run using the MATLAB runtime environment (Ver 9.7 Windows 64-bit) in the online workshop classes.

Outcomes and discussion

The virtual mechanics laboratory activity was successfully conducted during the online workshop classes across the 2020, Semester 2 cohort of over 600 students, working in groups of 3. Within a workshop class, students are allocated 90 minutes to complete the tasks in each of the experiment configurations (a) and (b), which are to determine the spring characteristics of a random spring and to predict the unknown weight of an object.

Table 1 summarises the outcomes from the 220 student groups within the cohort.

Table 1: Summary of outcomes from students conducting the virtual laboratory

Spring Scales Experiment	Outcomes	Average time taken to complete experiment
Configuration (a)	All 220 groups (100%) obtained spring characteristics within the acceptable tolerance of ±15% and predicated the weight of an unknown object within the acceptable tolerance of ±20g.	65 minutes
Configuration (b)	218 groups (99%) obtained spring characteristics within the acceptable tolerance of ±15% and predicated the weight of an unknown object within the acceptable tolerance of ±30g.	75 minutes

In successfully completing the two sets of virtual laboratory experiments, students have demonstrated their ability to:

- record a spring characteristic data set by applying varying load to a spring and taking measurement readings,
- plot a measured data set, determine a best fit line, and apply Hooke's Law principle to obtain the parameters that characterise a spring,
- set up a balanced spring scale, take the necessary measurement readings and apply either the mechanics principle of resultant force or resultant moment to predict the unknown mass of an object.

The learning objectives achieved from the virtual laboratory has tracked closely to the objectives of the original hands-on laboratory, thus validating that the virtual laboratory was equally effective in providing conceptual understanding of the relevant mechanics principles as the original physical laboratory previously. This is supported by studies from Triona and Klahr, (2003 and 2007) that suggest replacing physical laboratories with virtual laboratories does not affect the acquiring of conceptual knowledge.

From Table 1, a slightly higher percentage of groups produced results within expected tolerances for experiment configuration (a) and within a shorter completion time as compared to that of configuration (b). This observation is attributed to the additional angle measurement step and higher level complexity mechanics concepts required for the analysis tasks in configuration (b), which saw the increased average completion time and 2 groups failing to produce results within the time period allowed.

Overall observation on the time taken by students to complete the virtual laboratory experiments revealed that average completion time is shorter as compared to the equivalent physical experiments, which averages 90 minutes in previous semesters. To understand where the time discrepancies lie, the different natures of tasks performed in both the virtual and physical experiments are split into two distinct categories:

- Tasks that require performing an action - applying load and taking measurement readings
- Tasks that are analytical in nature - entering data, plotting graph, finding the best fit line, applying equations, and performing calculations.

In the author's opinion, the time taken to complete the analytical tasks in the virtual setting would not significantly differ from that of the physical setting due to the nature of these tasks that are not dependent on hardware or equipment, suggesting that the action tasks are the main factors for the shorter completion time in the virtual experiments. This is consistent with observations that measurements could be made with the click of a button in the virtual interactive GUI as opposed to the time required to set up and fine-tune or calibrate equipment in the physical setting. The virtual laboratory provided the environment for students to

experience all the procedures in conducting the mechanics experiments but was unable to offer hands-on laboratory skills such as planning equipment set-up, calibration, real-world experimental observation, and troubleshooting. This is where the affordances of virtual laboratory versus physical laboratory can be argued. Virtual laboratories offer efficiencies over physical experiment by providing more focus on the testing procedures and concepts without the unnecessary delays of experimental set up. (Ibrahim, 2011; Ton, Linn, & Zacharia, 2013; Klahr, Triona, & Williams, 2007). Additionally, it provides an environment for students to explore both practical and theoretical concepts with a wider selection of materials and specimen sizes, an example being the introduction of 4 different springs for use in experiments as opposed to the original 1 used in the classroom setting.

In terms of the usability, scalability and accessibility aspects that was part of the initial design considerations, all cohort groups managed to access and run the executable application within university resources without requiring additional external software or support during their respective workshop classes. The MATLAB Runtime environment to run the standalone executable was provided by the University's remote server, hence there was no need for students to download and install a separate software. It is worth noting that the virtual mechanics laboratory was subject to a series of usability testing by 10 tutors prior to its use in the online workshop classes. This was in accordance with Cooper's (2005) recommendation of usability testing prior to deployment to provide insights into the way in which users will interact with the software and the experiment, which cannot be foreseen by developers. Feedback from the pre-workshop testing exercise has proven valuable in improvement and fine-tuning efforts towards the successful end product.

The final consideration is how accurate the virtual experiments were in modelling after the physical ones. Whilst the ideal system behaviour was easily modelled using standard equations, real world experimental inconsistencies were not so easily replicated. Although the simplified random noise factor that was incorporated in the simulation may not the best representation of actual behaviour, it serves as an introduction to non-ideal behaviour and was a practical option under the given circumstances. This is an area that could benefit from more in-depth investigations.

Concluding remarks and recommendations

Given the limited time allowed for the transition from face-to-face classroom learning to online delivery, the virtual mechanics laboratory was a viable alternative that has provided first-year engineering students the opportunity to experience experimental procedures that demonstrated the intended mechanics principles. The virtual experiments offered efficiencies over physical experiments in terms of minimising experimental procedure delays and allowing more focus on concepts and theories but unavoidably compromising other hands-on experience such as equipment set-up, calibration, and real world behaviour.

For a more comprehensive virtual laboratory experience, future work should be considered in areas relating to real world practicalities such as:

- modelling a more accurate physical environment within the virtual laboratory to represent real world behaviour, to include physical modelling of spring dynamics to replace the simplified random noise factor and introduction of modelled frictional losses at the pivot joint of the spring scales.

- incorporating additional tasks or assessments in the virtual laboratory associated with awareness and appreciation of real world practicalities. With the excess time remaining from completing the prescribed experimental tasks, students could be provided with a video recording and empirical data from physical experiments for comparison studies.

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