Redesign of a first year engineering design course lab activity for remote instruction

Mr. Matthew Robin Kohanfars, UC San Diego

I am a mechanical engineering master’s student that is focused on encouraging students to seek engineering careers by developing entertaining and thought-provoking curriculums for the engineering department at UC San Diego. My master’s degree background targets the field of medical technology, where I am able to work in a design laboratory that specializes in researching and developing medical devices. I plan to continue my education to obtain a Ph.D., directing my impact on engineering education and translational research at UC San Diego.

Mr. Edward I Lan, University of San Diego California

Edward Lan earned his B.S in Mechanical Engineering from the University of California, San Diego in 2017. He moved on to work in the aerospace industry at Applied Composites San Diego (Formerly San Diego Composite) directly after graduating, developing new composite technologies devoted to applications for aerospace and defense through small business innovation research(SBIR) funding. In 2020, Edward re-entered the University of San Diego California to pursue a master’s degree in mechanical engineering, and is presently specializing in dynamic systems and control, material sciences, and bioinspired robotics. During his undergraduate career, Edward spent 2 years as an instructional tutor for an engineering design course and spatial visualization course at the University of California, San Diego. Presently he is working as an Instructional Assistant during his graduate studies, and is also working as an engineer designing robotic control methods for SBIR technologies at Dynovas Inc.

Dr. Huihui Qi, University of California, San Diego

Dr. Qi is an Assistant Teaching Professor in the Department of Mechanical and Aerospace Engineering at the University of California San Diego (UCSD). She earned her Ph.D. degree in Mechanical Engineering from Rutgers University-New Brunswick. Dr. Qi’s teaching interests include Engineering Design, Solid Mechanics, Mechanical System Design, and Computer-Aided Design. Dr. Qi’s areas of interest and expertise include design sustainability, Life Cycle Assessment, decision making for optimal design, and Computer-Aided Design and Engineering Education. Prior to her position at UCSD, she was an Assistant Professor at Grand Valley State University.

Tania Morimoto, University of California, San Diego

Tania K. Morimoto received the B.S. degree from Massachusetts Institute of Technology, Cambridge, MA, in 2012 and the M.S. and Ph.D. degrees from Stanford University, Stanford, CA, in 2015 and 2017, respectively, all in mechanical engineering. She is currently an Assistant Professor of mechanical and aerospace engineering and an Assistant Professor of surgery with University of California, San Diego. Her research interests include robotics, haptics, and engineering education.
Redesign of a first year engineering design course lab activity for remote instruction

Abstract

This paper presents the redesign of a lab activity for a first-year mechanical engineering design class at UC San Diego. The modifications implemented addressed the challenges faced by the COVID-19 pandemic and provided support for remote learning. This lab activity is called the Force, Torque and Power Energy (FTPE) analysis. This allows students to experimentally evaluate and understand torque, spring constants, moments, power, and energy for motors, springs, rubberbands, etc. with the use of a project kit provided. Proficiency of these concepts and evaluation skills are prerequisite for successful performance in a final robot project. Critical design constraints for the robot are identified through analysis of experimental data collected from the series of hands-on measurements. The results from the student calculations of the laboratory activity using the kit were compared to in-person measurements in a laboratory setting. Using these performance metrics, we were able to determine that the students were able to extrapolate their hands-on learned skills into more complex engineering applications in the form of a robot design. Although the work demonstrated in this paper is obtained through the FTPE lab activity, similar approaches could be taken that can expand remotely taught hands-on labs in future courses.

Introduction

Laboratory courses enable students with an active learning framework to improve their understanding of important engineering concepts such as force and torque. The kinesthetic aspect of designing, building, and testing gives students an intuitive sense of the principles that they learn in their theory-based courses, and provides an outlet to connect real-life experiences with theoretical ideas learned in class. Studies have shown that the application of the physical experience can enhance the learning of scientific concepts such as torque and angular momentum [1]. The work of C. Kontra et. al. finds that with active learning, students’ exposure to a physical interaction to forces that were associated with angular momentum correlated to an increase in quiz scores, as well as activation in the brain related to the sensorimotor region when reasoning about angular momentum at a later time. Other studies such as that of S. Freeman et al. [2] have also shown that through active learning, students gain the ability to perform better on tests than without active learning. Therefore, with the shift into a virtual learning space, it becomes imperative to maintain the kinesthetic learning aspect of laboratory based courses, to engage students, as well as to help them gain better conceptual understanding of ideas such as torque, force, etc.

In laboratory courses, group-based hands-on learning is also critical for students to obtain professional skills that prepare them for industry, such as effective communication, problem-solving, and decision-making. With the increase in globalization and the fast-paced
nature of the technology industry, it has become imperative that students not only learn essential engineering skills, or hard skills, but also professional, or soft skills, as outlined by A. Patil [3]. In laboratory settings, where students are expected to physically solve a problem, the experience of communicating with peers and building foundational intuition comes naturally. In a virtual environment, such an experience can be harder to maintain, and requires targeted assignments that encourage students to not only perform experiments and designs as an individual, but to also rely on a team for brainstorming and peer review.

The movement towards virtual learning during a global pandemic, has inspired laboratory courses to pivot by either re-establishing course learning objectives or redesigning in-person hands-on experiments for at-home implementation. Such redesign is difficult given that in-person laboratory courses that allow students to learn about concepts through kinesthetic learning, often require uncommon or custom equipment. This equipment can also often be expensive, bulky, and logistically impossible to implement in every student’s home. For example spring gauges for force measurements, while low cost, are not likely to be a household item for most students. Alternately, equipment such as a custom speed counter for a high-speed motor, could not only be expensive, but also bulky, and logistically impossible to fabricate and ship to each student. With the advent of the COVID-19 pandemic came the need to improvise and develop at-home laboratory experiments and projects that would allow students to experience a similar learning style to that of the in-person laboratory course, that would benefit students’ learning experience without the need for complex or high-cost instrumentation.

In an introduction to prototyping, engineering graphics, and design course, where students perform assignments and projects as a team, we focus on an assignment that gives a hands-on experience with the principles of force, torque, power, and energy. By building intuition on these concepts, and learning how to test and measure their properties, students gained a practical basis that helped them to design and fabricate a robot driven by DC-motors and elastic energy. The assignment, in its in-person form, provided teams of students with a set of energy and power sources that included high speed motors, geared motors, springs, and rubber bands, which made up a portion of a robot kit of materials that each team of students was given at the start of their final project. They were allowed access to an undergraduate design and prototyping studio, where they could use instruments such as force spring gauges, rotation counters for high speed motors, and a stall-torque measuring device. In addition to the plethora of equipment available, instructional assistants and peers would also interact to help guide teams through the process of determining the properties of their energy components.

When universities transitioned into online classes, the ability to perform the same projects and assignments was heavily restricted, and the course was redesigned to allow for students to reap similar benefits to the in-person version of the course. Modular kits with materials for fabricating robots and dynamic apparatus were shipped to each student. These kits included materials such as cardboard, foamcore, and nuts and bolts, as well as tools such as screwdrivers, drill bits, and exacto knives and were designed to allow for flexibility in both the design of the students’ final project robots, but also in allowing the instructional team to make
use of the components for hands-on assignments. The criteria for assessing the success of the redeveloped assignment was the distribution of students’ measured values using the supplied tutorials, as well as the minimized cost of the materials used.

**First-Year Force Torque and Power Energy (FTPE) Laboratory Activity Product and Procedure**

At UC San Diego, it was essential that students in an introductory mechanical engineering course gain a concrete understanding of the fundamental concepts of force, torque, energy, and power. To demonstrate these concepts, a project kit of materials and tools was utilized in conjunction with a tutorial assignment that engaged teams of 2-3 students. The learning activity was segmented into 2 parts and provided to students to teach them how to experiment and test mechanical attributes with motors, springs, rubber bands, and other additional components. These lessons were built on the testing principles illustrated in Figure 1. In the first learning experiment shown in Figure 1a, students analyzed a DC motor to determine its physical properties such as the torque at which the motor stalls, the no load angular speed, and maximum power output. In Figure 1b and Figure 1c students utilized more components of the kit to determine the physical attributes of springs and different sized rubber bands.

![Figure 1](image-url)  
Figure 1: (a) Illustration of DC motor testing setup and attributes to determine. (b) Depiction of spring analysis. (c) Configuration of rubber band setup analysis.

**Part I: DC Motor Testing**

To examine the DC geared motors, students utilized tools and materials from their robot kits that consisted of a screw driver, rubber bands, acrylic brackets, a battery pack, cutting mat, and large nuts to use as known weights, illustrated in Figure 2a. The assembly process for the setup in Figure 1 consisted of constraining the acrylic brackets to the motor, thereby creating a lever arm whose length was measured with a ruler printed onto the cutting mat. The nuts were suspended on a long screw placed at the distal end of the lever arm as in Figure 1a. The leads of the battery pack were then connected to the motor, causing the lever arm to rotate to an angle at...
which the motor could no longer supply sufficient torque to overcome the moment generated by the weight of the distal nuts. Students then estimated the angle of the lever arm with respect to the horizontal surface of the ground using one of two methods. The first method was by using a protractor to measure the stall angle, while the second method was to use the ruler provided on the cutting mat to determine the horizontal and vertical distances between the pivot point and use geometry to calculate the angle. Using moment equilibrium calculations about a point, students could then solve for stall torque. Given the weight of the components, the students would then run multiple trials and receive an average value of the stall torque of the motor. The system could also be used to determine the no load angular speed of the motor which is a quantity necessary to acquire for calculating the maximum power of the motor. The no load speed experimental calculation is begun by removing the mass present on the motor and supplying a current into the motor by connection of the motor leads to the battery pack. By observing the number of revolutions per second, the no load speed could be approximated. The students would then compare their results with the team to determine any associated discrepancy of their results, discuss their experimental setup, and fill out the assignment, calculating a final average for each quantity, allowing them to reinforce the team-learning aspect of the assignment.

Figure 2: (a) Motor kit used to test the properties of a DC motor(blue). (b) Complete assembly of motor experiment.

**Part II Spring & Rubber Band Experimentation**

In the second module of lessons, students utilized the properties of oscillatory motion in a spring mass system to determine the proper stiffness constants for the springs and rubber bands. Using similar components from Part I with the addition of a vise grip, string, and wooden dowel for constraining support shown in Figure 3, the students can begin their experiment to determine the properties of their spring components. The assembly is illustrated in Figure 4 and the process consisted of placing an acrylic plate into the vice to create a hanging platform for the springs to oscillate from. A bolt would then be used to attach either a spring or a rubber band to the hanging acrylic arm and a weight attached to the other end of the spring or rubber band. To create a
known weight at the bottom end of the spring component, students filled a plastic bag, that contained the screws and bolts from their robot kit, with parts of known valued weights. Because each kit consisted of the same materials, the kit components could be measured by the instructional team, and their weights posted for any student not owning a scale or balance to use in their calculations. The weighted bag could then be attached to the lower end of the spring by means of a bolt and nut through a hole in the plastic bag. For the calculation of the spring constants, the bags would be pulled down and released, causing periodic oscillations that students could measure with a clock or stopwatch and input into calculations to determine the spring constants. As an option, students could also utilize the wooden dowel in place of the bolt in the acrylic frame, and use a string to tie the mass to the spring component.

Figure 3: Content of the spring and rubber band kit that was used to assemble the experimental setup for analyzing spring and rubber bands of different stiffness constants.

Figure 4: Experimental setup of the spring system being performed. Similar setup was conducted for the rubber band test.
For the project kit to be economical for shipping to students, each component needed to be evaluated and compared to other researched products. The total cost of all the materials, as shown in table 1, was calculated at approximately $43.75 per individual. Each component was versatile in its use as following the design activity, all components were used for the students’ final robot project.

<table>
<thead>
<tr>
<th>Kit Part</th>
<th>Price Per Part</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting Mat</td>
<td>$4.75</td>
</tr>
<tr>
<td>Screwdriver</td>
<td>$0.98</td>
</tr>
<tr>
<td>DC Motor's</td>
<td>$7.90</td>
</tr>
<tr>
<td>Acrylic Parts</td>
<td>$0.15</td>
</tr>
<tr>
<td>AA Batteries</td>
<td>$1.00</td>
</tr>
<tr>
<td>AA Battery Pack Holder</td>
<td>$1.62</td>
</tr>
<tr>
<td>Rubberbands</td>
<td>$0.07</td>
</tr>
<tr>
<td>5/8in Nuts</td>
<td>$0.67</td>
</tr>
<tr>
<td>#8-32, #4-40 Round Head Screw and Nuts</td>
<td>$13.31</td>
</tr>
<tr>
<td>Springs</td>
<td>$3.64</td>
</tr>
<tr>
<td>Wooden Dowel</td>
<td>$1.68</td>
</tr>
<tr>
<td>Vise</td>
<td>$7.99</td>
</tr>
<tr>
<td></td>
<td>Subtotal: $43.75</td>
</tr>
</tbody>
</table>

Table 1: FTPE analysis kit contents and the associated price of each kit part.

**Results**

To determine the reliability of the setup and instructions in teaching students how to test and measure the correct stall torque and no-load speeds of Parts I, the final reported values of the properties of their components were examined and compared to the expected values. The distribution of the values calculated by the students in the stall torque calculation was Gaussian with a center shift left from the expected stall torque value as can be seen in Figure 5. The expected stall torque calculation was 0.14 Nm, and students generated a mean of 0.10 Nm with a standard deviation of 0.06 Nm. The shift from the expected value can be attributed to the variability of methods by which students measured the stall angles. Additionally, while performing the experiments it was discovered that by tightening the rubber bands around the backend shaft of the motor, some students would inadvertently stall out their motors prior to
reaching the actual stall torque. The no-load speed shows a similar trend, with the actual no load speed calculated at 11.1 rad/s. The reported final student calculations gave a mean of 9.0 rad/s no load speed with a 3.0 rad/s standard deviation, suggesting a systematic error causing the distribution to shift left, due to the excess number of occurrences at the no load speed of approximately 6 rad/s.

Figure 5: Stall torque and no-load speed student answer distribution with actual laboratory calculations shown for comparison.

For part II, the spring and rubber band stiffness constants show better centralization, with the peak of the Gaussian corresponding to the expected spring constant values as seen in Figure 6. The students were successfully within the range of the actual laboratory achieved value indicating that the experiment done in-home was consistently replicable. With the mean value of 74.96N/m and an actual value of 76.98N/m students have shown that the experimental setup of the kit was sufficient for calculating the stiffness constant of the rubber band. In the analysis of the spring constant of Figure 6, even with the slight deviation from the actual value of 50.97 N/m, students submitted results that were within a standard deviation of 12.50 N/m of the mean of 54.65 N/m.
Figure 6: Rubber band and spring stiffness constant answer distribution with actual laboratory calculation shown for comparison.

**Conclusion**

The redesigned FTPE lab activity has effectively provided a physical learning experience for students to conceptually understand the principles of force, torque, power, and energy. The distribution of students’ answers in comparison to the expected values shows the reliability of the assignment in teaching students to set up their own experiments at home. The mean and standard deviation of the stall torque at 0.10 Nm and 0.06 Nm respectively, deviated from the expected value of 0.14 Nm, and was likely due to issues in the accidental constraining of the motor shaft for some students. This design could be further improved with notes in the tutorial to prevent students from accidentally incurring an undesired friction force on the motor shaft. The no load speed followed a similar trend with a mean and standard deviation of 9.0 rad/s and 3.0 rad/s respectively, with an expected value of 11.1 rad/s. This error was likely due to the
method by which students may have measured the timing of the revolutions of their motors. It can be noted that at no load speed, without any arm weight or loading on the motor, finding the exact period can be difficult by eye and create a large error.

Comparatively the spring and rubber band portion of the activity provided more expected results. With a mean of 74.96 N/m compared to the expected value of 76.98 N/m, with the rubber band analysis, students were able to achieve a distribution centered close to the expected spring constant. For the spring activity, with a mean of 50.65 N/m and standard deviation of 12.50 N/m, compared to the actual value of the spring constant, 50.97 N/m, students were able to very effectively determine the correct spring constant.

Establishing an understanding of the concepts of the FTPE analysis were useful when the students needed to develop a more complex design with their final robot. These remotely conducted experiments enable the students to construct an experimental apparatus, gather results, and analyze their calculations. The calculations the students did to determine the maximum mass a robot arm could hold before stalling and their evaluation of the maximum velocities their robot could achieve was evidence of a complex understanding of the FTPE analysis. The success of these project kits can be translated into laboratories and courses that teach the fundamental concepts of engineering.

**Future Work**

In future studies, the implementation of pre and post assessments immediately prior to and after the completion of the assignment will provide an understanding of the conceptual growth of the student’s knowledge. As an alternative to written assessments, oral tests can provide a better evaluation of a student’s understanding of the key principles and can be used to verify the depth to which students have learned the key principles. As virtual learning spaces transition back to in-person environments, there also comes an opportunity to compare the capabilities of students’ ability to learn in the in-person laboratory setting to that of the online laboratory version. As the teaching space and the world continue to evolve, so too will this assignment and course, to better prepare undergraduate students for high level engineering careers and research post-university.
References

