Work in Progress: Developing Mechanics of Materials Skills through an Integrated Prototyping Project

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As a member of the Integrated STEM Education Research Center (ISERC) at LaTech, Ethan's primary research area is engineering design education with a focus on developing prototyping skills through both class-based projects and extra-curricular clubs, competitions, and activities. This includes a focus on hand-drawn sketches and how they are used as tools for generating ideas and visual communication, especially when it involves the skill to generate quick and realistic sketches of an object or idea. He has also conducted research on the impact involvement in academic makerspaces has on students in engineering programs.

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Abstract

Engineering students are often presented with problems of a constrained system and asked to find a specific value. However, many "real-life" problems encountered by engineers have no set procedure for finding the answer, causing the engineering to rely on intuition, creativity, and knowledge of physical systems to determine an appropriate evaluation procedure for each system. This situation requires the engineer to have the ability to design, fabricate, and evaluate a proper testing apparatus. However, many engineering curricula do not produce engineers with the skillset needed to develop this sort of instrument. This paper introduces a mechanics of materials project aimed to give students experience in creating ways to evaluate mechanical properties. This project requires students to pull knowledge from coursework in several areas, including civil engineering, mechanics of materials, basic circuits and controls, and communication. The students use these skills to construct a small tensile testing machine controlled by a microcontroller. The students program the microcontroller to drive a stepper motor to translate a linear shaft while simultaneously taking readings from a load cell. The students use their machines and measurements from their microcontrollers to test various mechanical properties of a chosen material.

Introduction and Motivation

For theoretically based courses such as statics, it is common for students to be taught in a primarily (or solely) problem-based format. Problem-based learning is focused on the students completing problems, often invented by the instructor, showing different situations and requiring the use of canned equations to determine a solution. Perhaps the classic example of this in a statics course is a planar truss (with weightless members) loaded in a variety of ways. However, these invented problems may not be similar to a problem encountered by a professional on the job [1, 2]. An alternative to teaching students via solely problem-based learning is the introduction of a project that required the student to apply their knowledge to an authentic circumstance.

A study by Lima, Mesquita, and Flores [3] found that students, educators, and engineering professionals all had a generally positive attitude towards the inclusion of project-based learning in curriculum. Furthermore, the inclusion of project-based learning has been found to have several positive impacts. Even though these projects generally take away from the amount of time dedicated to lectures, these tradeoffs do not detract from the understanding of course content, and students even gain a better ability to adapt their knowledge to new situations [4]. These types of courses have also been found to improve performance and retention at all levels of education [5–7].

Working on these types of projects has been shown to boost self-efficacy and career aspirations [8]. Self-efficacy (or a person's belief in their ability to complete a task) has been found to be a strong indicator of future success [9, 10]. Coincidentally, research has shown that teaching a project-based learning course improves the instructor's self-efficacy for teaching more effectively than teaching via lecture alone [5]. These courses have also been found to increase student intrinsic motivation (motivation from enjoying the topic they are learning) for certain students [11].

For all these reasons, more authentic projects should be included throughout the engineering curriculum. This paper introduces a project developed to help students learn mechanics of materials concepts. This project has students used skills gained from the freshman engineering series at Louisiana Tech University as well as topics learned during the course to construct and program a tensile tester. This tensile tester is then used to conduct tests to determine mechanics properties

Courses Utilizing Tensile-Tester Project

The tensile tester project has been implemented into two different courses. The first course is Statics and Mechanics of Materials. This is a sophomore-level course required for students in all engineering disciplines. The second course is Applied Engineering Mechanics, a sophomore-level course part of the controls and systems engineering technology program. Table 1 outlines the topics covered in each class.

Table 1. Course Topics in Approximate Order Introduced

Course Topics	**Statics and Mechanics of Materials**	**Applied Mechanics of Materials**
Resultant Forces	**X**	**X**
2D Concurrent Forces	**X**	**X**
3D Concurrent Forces	**X**	
Normal Stress and Strain	**X**	**X**
Shear Stress and Strain	**X**	**X**
Axial Loading and Deformation	**X**	**X**
Torsional Loading and Deformation	**X**	**X**
Torque Transmission through Gears	**X**	**X**
Rigid-Body Analysis	**X**	**X**
Free-Body Diagrams	**X**	**X**
Truss Analysis: Method of Joints	**X**	**X**
Truss Analysis: Method of Sections	**X**	**X**
Frames and Machines	**X**	**X**
Centroids	**X**	
Moment of Inertia	**X**	
Shear and Bending Moment Diagrams	**X**	
Beam Deflection and Flexural Stress	**X**	
Column Buckling	**X**	**X**
Pressure Vessels	**X**	**X**
Stress Concentrations	**X**	**X**
Finite Element Analysis	**X**	

Statics and Mechanics of Materials is part of a sophomore series of core engineering courses (along with Circuits and Thermodynamics) required for students in all engineering programs to complete. This course covers basic statics concepts and introduces mechanics of materials concepts. The course is taught in a lecture-lab style, meeting three times per week for an hour and fifty minutes for the entire twelve-week quarter. As the class meets for five and a half hours weekly, the time is divided between lecture, recitation, and project work. The amount of each of these varies week-to-week, but generally, there are 1-2 hours of lecture, 2-4 hours of recitation, and 1-3 hours of project work each week. The project work time gives students a dedicated time to work with their partners and the professor to address upcoming assignments or troubleshoot issues they may encounter. This course has an existing project which requires students to work in teams of two, three, or four to design and build a truss from hardboard. The students present their design with a brief presentation, and turn in a report that describes their design, provides an analysis of their truss including identifying members in tension and compression, and predicts where their truss will likely fail. This project has remained unchanged in the sections of the course that include the tensile-tester project described in this paper. In order to account for the added project, the students are given less homework based on the concepts covered in the lecture. This is replaced by homework assignments on for the project, as described in the following section. Additionally, the project-based version of the course includes only a midterm and final as opposed to three exams given in the problem-based version of the course. Presently, at Louisiana Tech, three sections of this class are taught each quarter (Fall, Winter, and Spring), with only one of these sections offering the project-based approach each quarter.

Applied Engineering Mechanics is part of one of the younger programs in the college, Instrumentation and Control Systems Engineering Technology (ICET). Being an engineering technology program, the highest mathematics course students take in this program is trigonometry. Thus, any use of calculus is omitted from the course. The course covers many of the same topics as the Statics and Mechanics of Materials course, with a few exceptions, as seen in Table 1. This course provides the only instruction into mechanics topics for the students in this program. Therefore, the goal of the course is to help connect statics concepts with instrumentation and controls applications. This makes the tensile-tester project an excellent addition to the course. This course is also taught using the lab-lecture style and thus meets three times a week for an hour and fifty minutes for the entirety of the twelve-week quarter. Courses throughout the ICET program tend to be more project-centered. Thus only the first 45 minutes of each class period are dedicated to lecture/practice problems with the remaining time dedicated to project work.

Tensile-tester Project Description

The goal of all our programs at Louisiana Tech is to produce engineers with the abilities needed to be immediately effective in the workforce and advance their fields through innovation. This project aims to aid in the development of several key skills crucial for becoming this type of engineer. Through incorporating skills learned from previous courses, especially courses in other disciplines, we hope to develop students' abilities to recognize how skills learned in coursework can be applied to a wide variety of situations. Additionally, through having the students build the tensile tester (as opposed to using one in a lab), we hope to help the students gain a better understanding of the pieces of information they need from a variety of disciplines in order to solve certain problems. Finally, through working in teams to develop a complex code, we hope to help students develop communication and cooperation. This project is broken into three main parts: an induvial assembly, a team assembly, and a final mechanics of materials report.

Individual Assembly

The project is presented to the students in a scaffolded format as homework assignments that steadily build on one another until the final iteration of the tensile tester is used for material testing. At the beginning of the quarter, each student is given a subset of the parts needed to build the final project. This kit is assembled by the project-based learning office and sold to the students at cost in lieu of a required textbook for the course. These kits include three pieces of extruded aluminum and the necessary brackets, bolts, and insertion nuts to assemble them, a sheet of acrylic with laser-cut holes (cut by the project-based learning office), a breadboard, tactile buttons, a stepper motor, and a motor driver compatible with an Arduino Uno microcontroller. The students are expected to own an Arduino Uno as the freshman engineering series uses them heavily for a series of projects; thus, all the students will have at least a year of experience writing code for Arduino projects. These individual kits are assembled to create a small assembly including the Arduino and stepper motor. An example of this smaller assembly can be seen in Figure 1.

The goal of these individual kits is to ensure that each student learns to control their own stepper motor before joining with a teammate. The first few homework assignments involve the students acquiring their kit and assembling the pieces with assistance from instructions on how to join the aluminum extrusions as well as circuit diagrams for properly wiring the motor, motor driver, and tactile buttons. After assembly, each homework is dedicated to learning to use the motor with increasing control. Initially, the students simply use a code that they can adjust between each upload to run the motor each direction and at various speeds. The students then develop a code that uses the tactile buttons to turn the motor in each direction. In the next assignment, the students create different "modes" for the motor. In "Jog Mode," pressing one button (Button A) causes the motor to turn quickly. In "Test Mode," pressing Button A causes the motor to move more slowly. The other button (Button B) is used to toggle between Jog Mode and Test Mode.

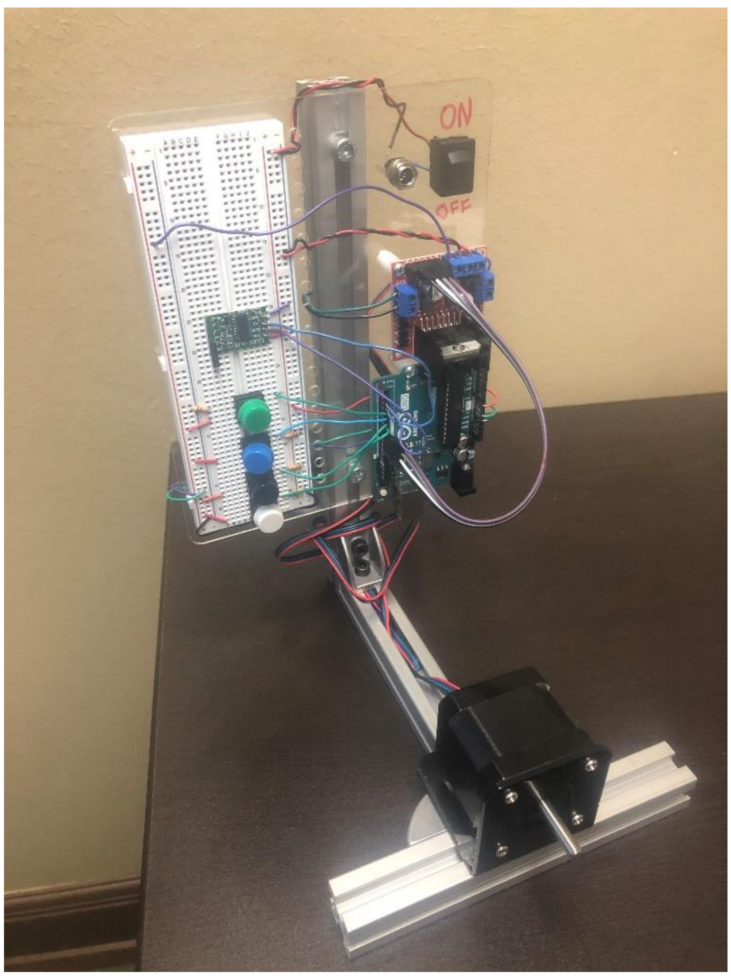

Figure 1. Individual Kit Assembly

After learning to use the tactile buttons to turn the motor in various ways, the students then create a code to track the angular position of the stepper motor. This is achieved by including a counter in their code that adds or subtracts to the current position based on how many steps the motor takes. The students use this knowledge to develop a code that allows the motor to rotate a set distance with the single touch of a button. Each assignment is meant to build in new functions to the code incrementally to each the student from having to create a complex code from scratch.

Over the first few weeks, students also become familiar with how to use a 3D printer that is available to them and are assigned to draw a bushing holder, a stabilizing piece for the linear shat, and two gears using CAD software. These parts are printed and used in the final assembly. These assignments include learning to use a program to convert their CAD files to the gcode needed for the 3D printers. These parts needed for the final assembly are assigned to be printed at different times to allow students ample time between prints and ease the demand for the available printers.

While the students are learning to control their motors using code and tactile buttons, they are given a small lab assignment to determine the amount of torque their motor is outputting. Using a leather strap, two spring scales, and a shaft extender for their motor, the students measure the torque output using the setup seen in Figure 2. The students run their motor at varying speeds and observe the force measured by the two spring scales. They then measure the torque of the motor using Equation 1, where T is torque, F_1 is the force readout by one of the spring scales, F_2 is the force readout of the other spring scale, and r is the radius of the shaft extender.

$$T = (F_1 - F_2)r \tag{1}$$

By comparing the difference between these two forces, the students observe how much force is added strap by the motor and convert this to torque using the radius (moment arm). The students vary the speed of the motor and observe the impacts this has on the torque. They then use the angular velocity and torque to determine the power of the motor. This lab coincides with the lecture about torsional loads.

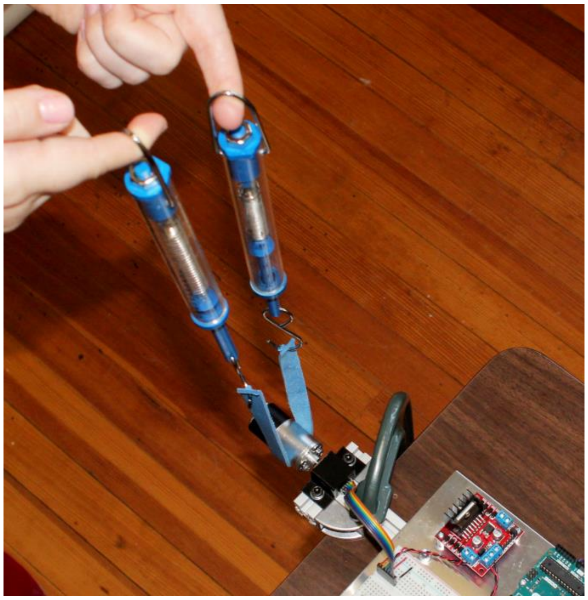

Figure 2. Motor Torque Testing Setup Using Differences in Linear Force Due to Friction

Team Assembly

After the students have mastered controlling their motors with their code and tactile buttons, teams of two (or three, if needed) are formed to move into the next portion of the project. Each team is loaned a “team kit” that includes a load cell, a load cell amplifier, a threaded rod, and some additional extruded aluminum pieces. With the pieces given to them in their individual kits, each team constructs their tensile tester frame. A provided nut is screwed onto the threaded rod and sits in the middle of one of the 3D-printed gears, which then sits between the 3D-printed bushing holders and is driven by the second gear attached to the stepper motor. Figure 3 shows the tensile tester fully assembled.

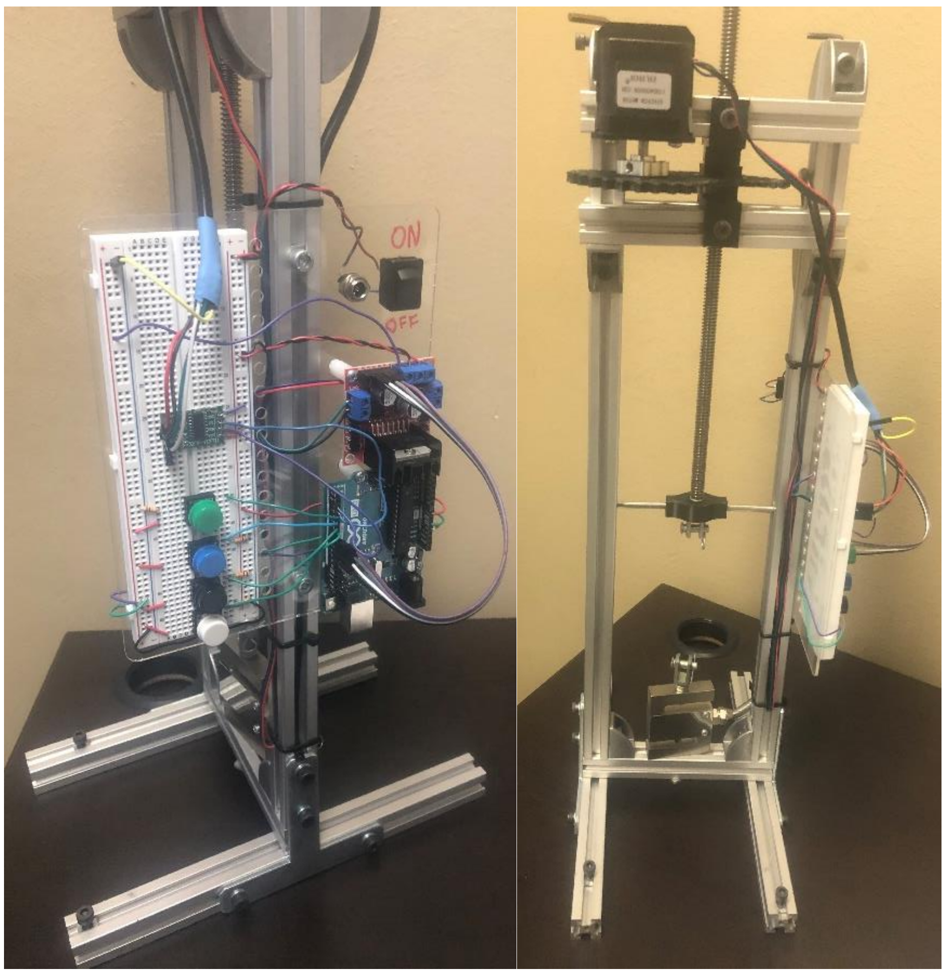

Figure 3. Assembled Tensile Tester Project

After assembly of the tensile tester, a homework assignment is dedicated to wiring the load cell and load cell amplifier properly. An additional homework (and a large chunk of a class period) is dedicated to calibrating the load cell. Once these are completed, the teams work on adapting their codes to control their motor to control their assembled linear actuator. This includes the addition of two buttons (each student had two, a total of four per team), and converting their motor’s angular position to the linear position of the end of their threaded rod using their gear ratio and lead distance of the threads. Ultimately, they are to develop a code that accomplishes the following:

1. The tensile tester should have two modes
    a. Jog Mode
        i. Buttons A and B should move the rod up and down quickly
    b. Test Mode
        i. Buttons A and B should move the rod slowly up or down to a pre-set distance
        ii. While the rod is moving and after it reaches its set distance, the serial output of the Arduino IDE should give a frequent readout from the load cell.
2. Button C should toggle between Jog Mode and Test Mode
3. Button D should act as an “Emergency Stop.”
    a. If pressed, the tester should immediately stop moving and require a system reset to be used again.

The students are to demonstrate their system working correctly and are graded for how well the system works and how cleanly their tester is assembled and wired.

Mechanics of Material Testing and Report

After the students have their functional tensile testers, each team is to select a material to test. The material is left up to the student, but they are encouraged to use a relatively ductile material that can fit within their assembly’s frame. Examples of some materials chosen include electrical wire, guitar strings, human hair (given from a willing participant), and 3D-printed dog-bone specimen. The students are tasked with loading their chosen material into their testers and loading them to various lengths based on their code’s ability to move the tensile tester a set distance. The readout from the load cell is then read, giving a length and force for each data point. This process is repeated several times (a minimum of ten, with at least five unique lengths) to create a data set for their materials. This data is then converted to strain and stress using the geometry of the tested specimens and plotted on a stress/strain chart. Students use this data to determine what the modulus of elasticity is for their chosen material.

In their written report, each team is asked to describe their tensile tester assembly, their code, and their analysis of their chosen material. In their description of the assembly, the report should include annotated pictures highlighting important parts and describe how their system mechanically works. This section should also include a detailed circuit diagram of their entire system. In the description of their code, the report should outline the “flow” of their system, dictating how where the Arduino is getting information from, how it is responding to those inputs, and what outputs are going back into the system. The final section should describe the team’s methodology for analyzing their chosen material and present their collected data. Based on their data, the students should state their material’s elastic modulus. Students are also required to research what the material’s elastic modulus should be from a reputable source (i.e., textbooks, academic papers), note the difference between their calculation and the value gained from research, and discuss what may cause these differences. There is typically a large difference between the modulus that was found experimentally and the modulus found through the students’ research. Some students recognize that a large part of this disparity is the system’s inability to recognize when the motor has slipped due to too large of a force. Some teams correct this by measuring the vertical distance moved directly instead of relying on where the system’s reading. This could be corrected by the inclusion of an encoder, but this has been avoided in the class as it would take more time to learn to code and ultimately does not add to the students’ knowledge in mechanics of materials. Instead, the project is meant to deepen students' understanding of the elastic modulus calculation and why their experiment may be off.

Future work and Analysis of Impacts

To date, this project has been taught in two iterations of the Statics and Mechanics of Materials course and two iterations of the Applied Engineering Mechanics course. No formal evaluations of the project or the impact it has on the students has been conducted, but student feedback on the project has been generally positive outside of some complaints about the amount of work as the project continues refinement. This complaint has been addressed by reducing the number of scaffolded assignments for the project to allow the students more flexibility.

In future work, a research team investigating the development and impacts of project-based learning courses plans to evaluate this project through a mixed-methods study. The impact of the project, as perceived by the students, will be partially evaluated through a case study of each course as the project is being carried out. This will be evaluated with the help of education research with experience in qualitative research methods. Additionally, the evaluation of the impact this project has on the students' learning of the course material, as well as additional impacts, is planned to use several quantitative methods. Currently, most sections of the Statics and Mechanics of Materials course are being taught without the inclusion of this project. These sections will serve as a pseudo-control group for quantitative analysis. Planned measurements for how well the material of the course will be understood include giving similar problems on exams given in each section and comparing scores. Additionally, a statics concept inventory will be used to determine how well each section improves students' understanding of the material.

As stated in the background section, the inclusion of project-based learning has been shown to improve self-efficacy for engineering and communication skills. Thus, self-efficacy surveys will be given to students in each section. It is also hypothesized that project-based learning may better improve retention of knowledge long term and retention with STEM programs. To capture these impacts, a cohort of students who complete this project will be tracked as they advance through the curriculum at Louisiana Tech, and their knowledge and self-efficacy will be re-assessed yearly.

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