# Board 34: Design and Prototyping of two different Mechanical Testing Instruments

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# Design and Prototyping of two different Mechanical Testing Instruments


## Abstract

The modern human society is largely being faced with complex engineering challenges that are not confined to any particular engineering or science discipline. These problems require innovative solutions with a multidisciplinary approach which draws on various concepts and knowledge base in an iterative process. The 'Engineering Clinics' at Rowan University a design infused, multidisciplinary, eight-semester sequence of courses in the College of Engineering. Inter/multi-disciplinary student teams engage in laboratory hands on activities focused on solving real world problems related to automation, additive manufacturing, embedded systems, renewable energy, artificial intelligence and biomedical technology to name a few. The aim is to prepare the students for highly evolving, competitive marketplaces. It also serves as an excellent testbed for conceptualizing and iterating engineering innovation and research.

This paper will discuss two projects where multidisciplinary groups of students develop prototypes of testing instruments. Project 1 involved designing a pharmaceutical vial seal force tester in collaboration with a local equipment manufacturing company. Seal force is the integrity of the sealing quality of the rubber stoppers that cap the pharmaceutical drug vials. The usual process of testing it is by performing a compressive test. The entire prototyping was accomplished in various phases. Project 2 was an independent undertaking that was conducted over a period of 2 semesters during which the student-faculty team conceived and developed an idea for marketing a low-cost mechanical testing equipment. The idea was to build a tensile, compressive tester using off the shelf component, keeping the selling price below $2500 per piece. The end users were initially targeted to be academic institutions and low strength material testing industrial customers. The paper will describe the device design and development process and resulting ABET student outcomes achieved.


## Introduction

The success of STEM education will depend on the ability of future generations of students to make the world better by devising innovative and creative solutions for improving the living conditions of all mankind. In recent years, emphasis has been placed on creating and adopting clean technologies worldwide as well as making the United States a manufacturing powerhouse once again. The success of STEM education will also pivot on the society's ability to create STEM based jobs in areas such as manufacturing. Mechanical Engineering and Material Science are two dominating disciplines in STEM education.

Recent technological advances and innovations in industry have witnessed a heavy reliance towards adoption of an interdisciplinary approach for solving some of the major challenges facing the manufacturing sector today. The highly competitive skill set requirements for employment of an engineering graduate today has broadened to an extent where only the candidates with a broad experience in multiple engineering disciplines stand to have a competitive edge over others in the pool. Engineering educators must on their part strive to provide ample opportunities to the students for broadening their skill-set by having them work on hands-on multidisciplinary design projects right from the start.[1],[2] The proposed project aims to accomplish this as one of its objective. With rapid progress in Material Science since early 21st century there is an unarguable need to arouse the curiosity of the younger generation from an early age so that they are well poised to become leading researchers and educators in this field. The purpose of this work was to provide the students with an opportunity to engage in laboratory hands on activities in an atmosphere that mirrors real industrial environment. It was envisioned this would provide real world STEM skills to the students in designing, fabricating and testing of an electromechanical system. The student teams would engage in frame and body design, drive system, real time data acquisition system design, human machine interface design, finite element stress analysis, and data processing system design. We discuss two projects here, both of which involved designing and prototyping mechanical testers. Project 1 involved designing a pharmaceutical vial seal force tester in collaboration with a local equipment manufacturing company. Seal force is the integrity of the sealing quality of the rubber stoppers that cap the pharmaceutical drug vials. The usual process of testing it is by performing a compressive test. The entire task was distributed between mechanical and electrical engineering students. Project 2 was an independent undertaking which was conducted over a period of 2 semesters during which the student-faculty team conceived and developed an idea for marketing a low cost mechanical testing equipment. The idea was to build a tensile, compressive tester using off the shelf component, keeping the selling price below $2500 per piece. The end users were initially targeted to be academic institutions and low strength material testing industrial customers.

**Brief Project Descriptions**

The development of the two clinic projects was as follows. For Project 1, we were approached by a local pharmaceutical device company to redesign a testing device for them called the **'residual seal force tester'** in the Spring of 2016. The purpose of the residual seal force tester is to determine the seal quality a pharmaceutical vial by measuring the stress, a compressed elastomeric closure flange exerts on a vial land seal surface after application of an aluminum seal (crimping) of the vial (see Fig. 1). The extent to which the elastomeric closure flange is vertically deformed against the vial land seal surface by the applied aluminum seal is referred to as the closure compression. The residual seal force value is the minimum of the 2nd derivative of the stress-strain compression curve. The tester is used as a quality control device in parenteral vial sealing.

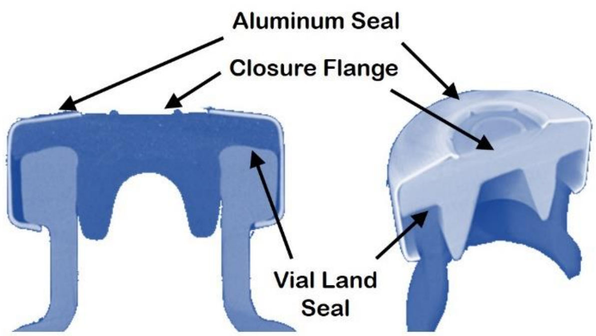



**Fig 1.** X-ray imaging of the mid-planar section (*left*) CAD representation (*right*) of a sealed vial[3]

The stopper is compressed, and an aluminum cap is crimped on top of it to hold the stopper in the compressed state. This creates a trapped force, as the rubber attempts to return to its original relaxed state and is what contributes to the residual seal force. The higher this force is, the less likely a vial is to leak. The student teams who worked on this project consisted of both Mechanical and Electrical engineering students. The initial semesters were spent understanding the science of RSF testing, the design of the current machine, and identifying areas where the machine could be improved. During the summer the student team interned in the company and was tasked with researching elastomeric properties associated with the sealing and testing processes. This helped the students gain a better understanding of elastomers. Following semesters were spent learning to program logic controller (PLC), switching the load cell type and configuration, and redesigning the electronics to match with the new load cell and updated testing requirements.

Project 2 was conceived by a couple of Rowan MechE faculty as a teaching aid for a Material science based courses being taught at universities and high schools. It was intended to serve as an affordable alternative to the costlier uniaxial tensile testing machines available commercially. The goal of the device was intended to be both, laboratory based teaching activity as well as research related requirements. The intended users were expected to be high school students, two-year junior college students, four-year undergraduate university students and graduate students taking mechanics or material courses. With the cost price of around $2500 per unit, the development of such a device would require the teams to draw extensively upon their knowledge of mechanical design, material behavior, programmed instrumentation control, data acquisition, shop fabrication, engineering economics, and entrepreneurship skills in order to successfully fulfill the task. This project was initiated in Fall 2016 with just a single electrical engineering graduate student on the team. The following year in Spring 2017, two mechanical engineering undergraduate students joined the team and then on the team size remained constant at four students. Here the project progress was spread over 4 semesters. Both projects are described in greater detail below.

**Residual Seal Force Tester**

Residual seal force (RSF) is the force that a compressed rubber closure exerts against the vial finish after capping. This force can be related to the quality of the seal on a pharmaceutical vial. During an RSF test, a compressive load is applied at a constant rate to the top of a sealed vial. There is a reactionary force of the stopper and aluminum cap that resists the compressive force, this is the residual seal force. The initial deformation measured is the deformation of the aluminum seal. Once the stress reaches a certain point, the measured deformation is that of both the rubber closure and the aluminum seal. The next segment of deformation corresponds to the lower portion of the aluminum seal beginning to move away from the lower lip of the glass vial. Any deformation measurements beyond this relate to the viscoelastic compression of the rubber stopper. The RSF value can be determined graphically when the stress-strain curve is plotted and the double derivative is graphed. There is a transitional point (referred to as a knee on the plot) where the deformation switches from the combined deformation of the aluminum seal and rubber stopper to the elastomeric response of the stopper at which point the slope of the graph drops and the plot proceeds in an almost linear fashion. The measured RSF value correlates to the measured stress at this knee. Figure 2 shows a plot depicting the RSF test.

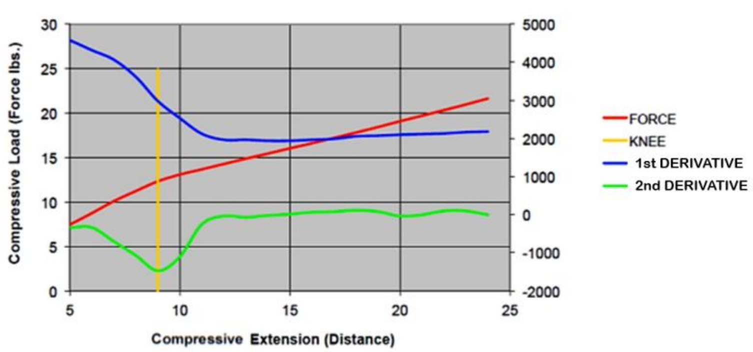



**Fig 2.** RSF test plot

The component of the machine applying the mechanical load is the loading arm as shown in Figure 3. A linear actuator moves the arm. At the end of the arm is a removable rod which can be replaced with rods of different lengths to account for different sized vials. This flat end of the rod makes contact with a round top (anvil) placed on the vial cap and serves as the point of force application. The force applied to the anvil results in its uniform distribution around the stopper's edge, where the rubber meets the glass vial.

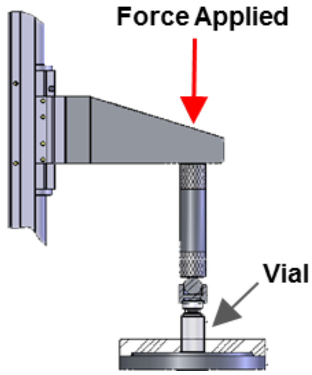



**Fig 3.** Measurement arm of the tester.

The main design objectives of this clinic project was as listed in Table 1 below.

**Table 1.** The main design objectives

| ITEM | Design Objectives |
|---|---|
| Load Cell | Reduce the capacity from 2000-lbs to 200-lbs and change the configuration, from being located at the vial base (bottom) to being located on in the loading arm (top). |
| HMI Interface | Replace the original Allen Bradley HMI interface to Proface Interface |
| Data Acquisition | Switch Data acquisition ports from RS232 to a USB or Ethernet |
| Noise | Reduce noise in data. |
| Accuracy | Improve accuracy (Original device had 10-15% error) |
| Pencils | 2 |
| Highlighter | 2 colors |
| Scissors | 1 pair |

Some of the major components of the tester are listed in Table 2 below.

**Table 2.** Parts List

| Item | Section |
|---|---|
| 24V, 100W Power Supply | |
| PLC, Compact Logix L23E | PLC |
| Analog input card | |
| PLC stepper card | |
| Step Motor | Motor |
| Step Motor Driver | |
| Digital Encoder | Encoder |
| Linear actuator | |
| Load cell | Load Cell |
| Load cell signal Amplifier | |

A significant portion of the project time was spent working with the Programmable Logic Controller (PLC). The PLC was programmed using the RSLogix 5000 code. RSLogix 5000 package is a design and configuration software for discrete, process, batch, motion, safety, and drive-based applications (see Fig. 4 *left*). It has a ladder logic, structured text, function block diagram and sequential function chart editors and provides a common environment for users programming the Allen-Bradley® ControlLogix® and CompactLogix™ controllers, in standard and safety configurations (see Fig. 4 *right*).

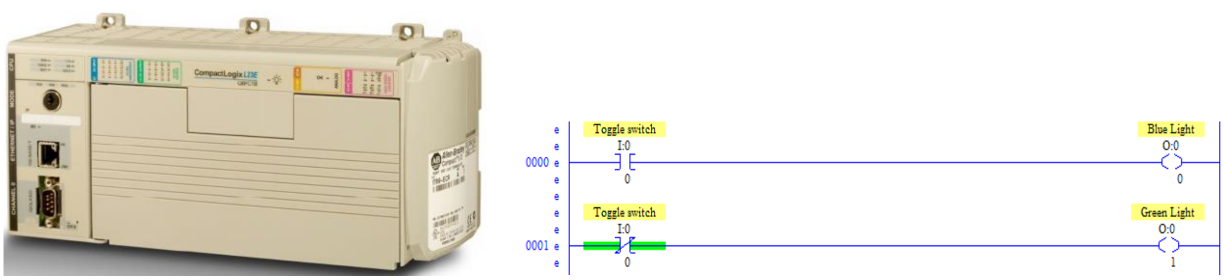



**Fig 4.** The CompactLogix PLC (*left*) and Ladder Logic sample code (*right*).

The base PLC had four different modules, also referred to as cards, each made to perform specific tasks. These four modules are DC input, DC output, analog input/output, and a high-speed counter. Both the DC input and output modules were only digital, meaning these modules could only understand a 24V input or output a 24V supply. Anything less than 24V would not be read as an input. The output was fixed at 24V, as this was the power supplied to the PLC. Half of the module could be wired to receive voltage between 0 and 24V, and the PLC converts this to a 16-bit value. The resolution of this reading is 40 mV. The other half of the module allows for an analog output, which can be programmed to output anywhere from 0 to 24V with the same resolution as the input. This module was originally used to power the load cell with 10V of power, and to read the amplified output of the load cell. It was found that this module's output voltage was not consistent enough, as an output of 10V was found to fluctuate between 9.5 and 10.5 volts. In the final base module, a high-speed counter (HSC), was utilized with an encoder to record the movement of the motor. It outputs a certain number of pulses every time the motor moves. Since a digital input module would not be able to accurately count these pulses, so an HSC module was usually used.

Load cell: A strain gauge based load cell was included to measure the load applied to the vial. The force limit was kept under 55lbs to prevent the glass vial from shattering. The device typically was designed to apply around 35lbs force. Strain gauge based load cells are known for their stability with static forces. The load cell, LC201-100 shown in Fig. 5 (*left*) was chosen. A DRF-LC load cell signal conditioner (Fig. 5 *right*) sold by Omega was used to condition the load cell signal. It allowed to convert process signals (load), to voltage signals for further retransmission.


**Fig 5**. Omega Load cell (*left*) and signal conditioner (*right*)

Motor: A stepper motor with 200 steps, each step being 1.8 degrees of rotation was used along with a linear stage as the actuator. The motor moved a step each time it receives a pulse of power. By moving in steps, the motion of the motor was not as smooth as a servo motor would have been.

**Prototype Fabrication**

A Solidworks model, Fig. 6, of the device was created. The design was made to be easy to access the inner electronics while keeping them sealed and having a relatively small footprint. The entire electronics was sealed into a box which would act as the base of the machine with the tester frame and control box mounted on top this allowed for easy access to the electronics inside. The prototype (Fig 7a) was made using primarily 80/20 aluminum extrusion, ¼" aluminum plate and ¼" black acrylic plates. These materials were chosen due to their ease of use to machine. The control panel was also designed as shown in Figure 7(b) and was comprised of 6 buttons and 2 knobs that were used to jog the arm, start a test, pause a test, emergency stop, adjust speed and adjust target force.

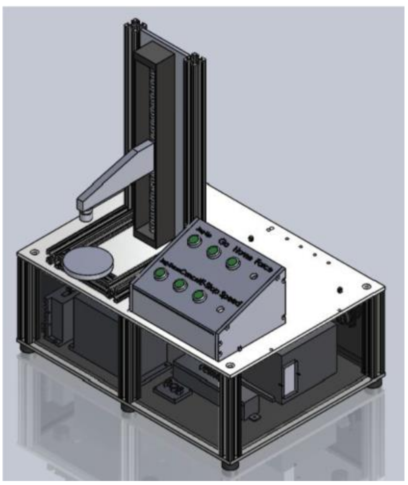


**Fig. 6** Solidworks prototype

**Fig 7 (a)** Final Tester prototype


**Fig 7 (b)** Control panel box

**Low Cost Portable Tester Fabrication**

The components that were used for this tester were mostly off the shelf components. We modeled our initial design using SolidWorks (see Fig. 8). The design consisted of three main features: support base, the back plate, and the testing platform. The support base was designed to support the load of the stress test from underneath and contain all of our electrical components. Components such as an Arduino board, stepper motor, power 300mm Linear Travel Stage source, and others were all placed and secured inside here. The components are shown in Fig. 9. Side panels could be unscrewed from either side of the support base to access or modify these components. On the front of the support base we developed a user-friendly control panel (see Fig 10) which had an on/off button, up and down buttons, and increase and decrease speed buttons.

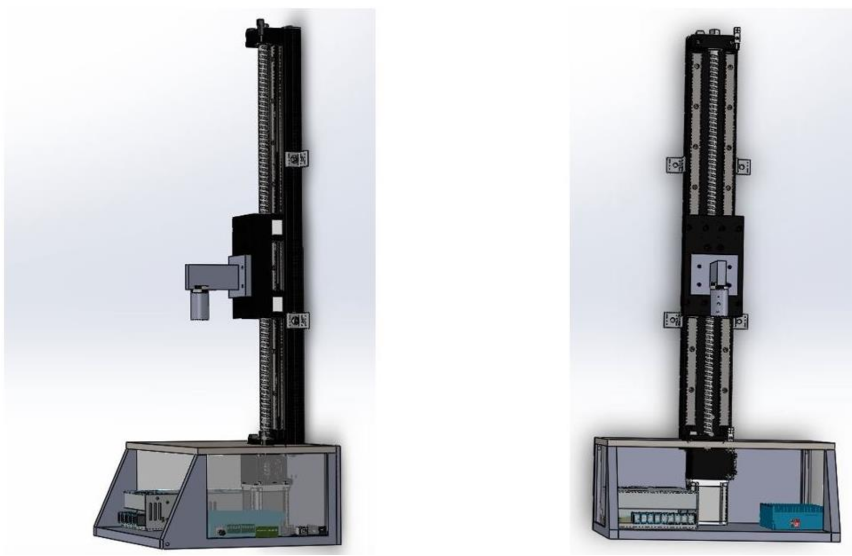
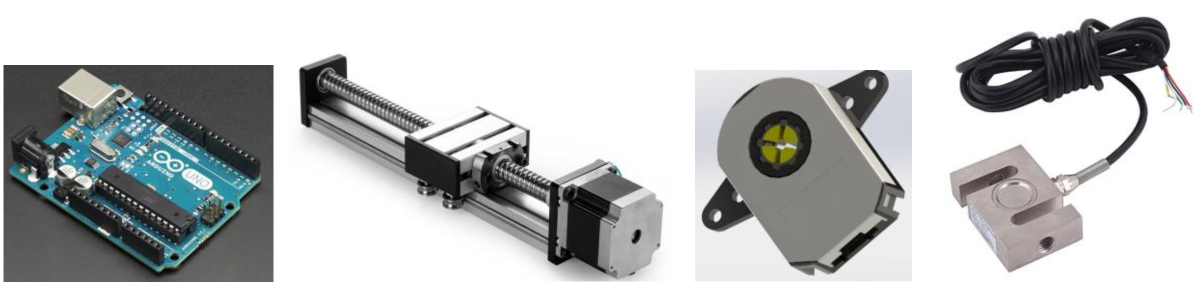


**Fig. 8** CAD assembly of the portable mechanical tester



**(a)** **(b)** **(c)** **(d)**

**Fig. 9 (a)** Arduino **(b)** Nema23 Stepper motor linear stage **(c)** AMT10 modular incremental radial encoder, **(d)** S-type Beam High-Precision Load Cell


**Fig. 10** Control panel

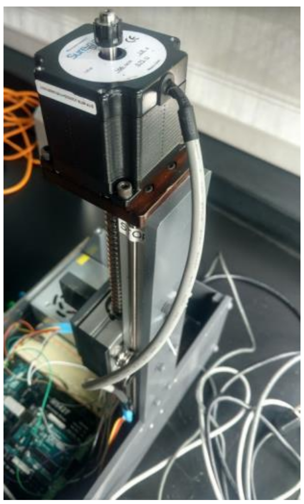


**Fig. 11** Back plate

The back plate (Fig. 11) had to be specifically designed to attach to the travel stage linear actuator. We also had to make sure the back plate and actuator could support the torque of a stress test and had to be secured to the support base and testing platform. The testing platform provide structural integrity for a material to be tested on. Table 2. lists a brief description of the components.

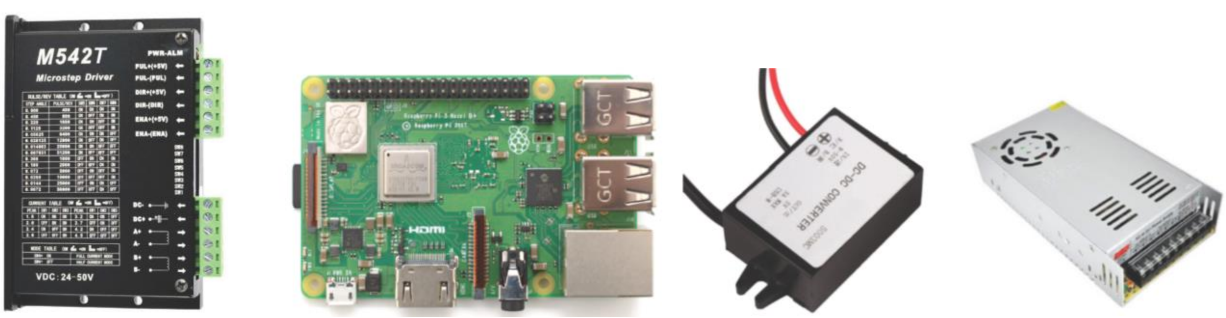
**Table 3.** Brief Description of the components

| Component | Description |
|---|---|
| Arduino | Programmed to control the stepper motor during testing, acquire load cell and encoder data. Connected to a computer to provide real-time flexibility. |
| Linear Stage | 300mm linear travel module, with a positioning accuracy of ±0.05mm, capable of axial load capacity =90lbf, normal load capacity =40lbf, and provides the support for an extension or compression test mechanism. |
| Load Cell | Portable S-type Beam High-Precision Load Cell Scale Sensor 50/100/ 300/2000 KG for Hopper Weight High Pressure Tension Weighing(300kg) |
| Encoder | AMT10 modular incremental radial encoder, resolution up to 2048 pulses/revolution, CMOS outputs, measures strain undergone by sample |

The device’s main goal was to be able to move in the vertical direction in order to perform desired testing while keeping track of the displacement. Therefore, a stepper motor was used to rotate the linear actuator. A Raspberry Pi was later added in addition to the Arduino. While the Arduino controlled the movement of the linear stage, the Raspberry Pi was exclusively used for performing mechanical testing. With ‘Python’ programming the stepping was controlled to achieve desired positioning and/or speed control. Rather than building the code to operate the stepper motor and potentially damage it, it was decided to first make a mock code that would simple control three LED’s. The first light would indicate if the system was on the second would blink at varying rates to indicate moving up and the rate would indicate the speed and the third is similar to the second but for the down button.

The team also used an encoder to track the motor’s precise position. An encoder also called a shaft encoder is an electro-mechanical device that can converts angular position of a shaft and translate it into analog or digital signals. Initially it was thought to use the stepper motor and track its position using steps made per revolution, but eventually it was decided against the idea as it was noticed that steps were being skipped with high forces/loads.

Micro stepping allows a motor to make far more steps per revelation. This is done by using a micro-stepping device along with algorithms developed by manufactures to send partial pulses to the motor which in return makes a very finer step. The device comes with three input pins, pulse, dire, and ena. For the purpose of this project pulse and direction inputs were used. In order to move the motor one step, a 5V signal was sent. Direction of rotation can be controlled by activating/deactivating a 5V signal on the pin attached to the direction input on the stepper motor. The other accessories are shown in Fig. 12 below




**(a)** **(b)** **(c)** **(d)**

**Fig 12(a)**. Micro stepper unit **(b)** Raspberry Pi **(c)** DC voltage converter **(d)** Power Supply

After getting the main electrical and mechanical components of the mechanical tester, we needed a power supply that can power all the devices. We choose a 24-power supply since the micro stepper requires 24V input. However, the Raspberry Pi was used to power all other electro-mechanical components such as the load cell 5V input, and the encoder which also requires 5V. As a result, 2 power connectors were plugged in to power outlets. The team decided to purchase a 24V to 5V convertor.

The tensile grips were then manufactured as shown below and were thought out to have a simple and inexpensive design. Fasteners were used to support the testing material Two of these grips had to be manufactured, one attached to the load cell and one to the base plate, to secure the testing samples. Fig. 13 shows the shape and size of the tensile grips, excluding the screw used to hold the sample in place.

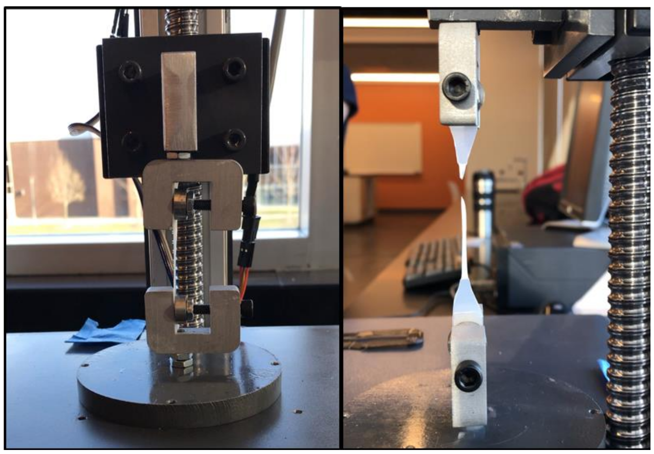


**Fig 13.** Tensile Grips

A large portion of the work also consisted of programming the mechanical tester. While developing the master circuit diagram and using it to construct the electrical setup, Python code was used to run the motor, rotary encoder, load cell, and buttons as well as a preliminary GUI was also developed. We built the machine so that it was able to perform a stress test, but have not collected measurements or calibrated its accuracy at the current stage.

## Conclusions

Overall the students learned a lot of hands on skills in this effort. Some work is still continuing so information has not been disclosed. Overall students worked in multidisciplinary team to complete the design, build, analyze, and test process for each of the two mechanical tester projects.  One project came from an industrial sponsor, and students were exposed to a real-world application.  The second project was derived from faculty and student interest to develop a low-cost, portable tester. Students sufficiently met ABET outcomes such as designing a system, using modern tools, recognizing consequences of engineering solutions on society, working in teams, and effectively communicating. Table 4 lists the assessment of some ABET objectives that were carried out.

**Table 4.** Assessment of the ABET objectives

| **ABET OUTCOMES** | **Residual Seal Force tester** | **Portable Mechanical Tester** |
|---|---|---|
| | scores out of 5 | scores out of 5 |
| 1.1 will posses the ability to apply broad scientific, mathematical, and engineering knowledge in order to be able to identify, formulate and solve problems in thermal or mechanical systems. | 4 | 4 |
| 1.2 will be able to design a system, component, process or experiment and analyze and interpret data | 4 | 4 |
| 1.3 will be able to use modern tools, hardware and software in problem solving process | 3 | 3 |
| 2.1 recognize the need for professional and ethical responsibility | 3.5 | 3 |
| 2.2 recognize and consider the consequences of engineering solutions on society | 2.5 | 2.5 |
| 2.3 will be knowledgeable of contemporary issues | 3 | 3 |
| 3.1 will be effective communicators | 4 | 4 |
| 3.2 will work effectively in multidisciplinary teams | 4 | 3.5 |
| 4.1 will recognize that learning is a continuous process | 4 | 3.5 |
| | | |

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