SMAPZT

A shape memory alloy wire actuator coupled with a piezoelectric sensor for actuation with controlled force

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Designed, Modeled, and Fabricated as a Final Project for:
ME475/575 Adaptive Materials and Systems

Presented to:
Dr. Constantin Ciocanel

Introduction

When presented with the challenge of creating a system that utilized smart materials, and our goal was to create a system that utilized multiple smart materials to actively apply a specified force. It was determined that for our design the coupling of an SMA wire actuator and a PZT sensor would accomplish our task. Since SMA actuators are a good candidate for artificial muscles it was proposed that we make a simulated finger. The finger would need to touch down on the sensor and quickly obtain a specified force that could be specified by the operator. It would also need to return to its original position each time the operation was stopped. Our goal in all of this was to demonstrate the possibility of precise force and position control of a simple joule heated SMA wire.

Approach

When the project was originally presented to the team we sat down and had a conversation as to what we should make and create. The team was really interested in having the two different smart materials combined into one project. This would allow us to experience the aspects of both the SMA and the PZT and get more hands-on experience with these materials.

The design process started with the desire to include both pieces and to achieve this a few ideas came to mind. In our proposal report we discussed a crane idea where we would use the SMA wire to lift weight and we could see how much was lifted by using a PZT sensor at the bottom, as a pseudo scale. We steered away from this idea for the lack of real work application. This is never something that would replace current technology. The other design that the team came up with was to use SMA wires to accurate finger, and to see how much the finger moves we would use a PZT as a way to create a feedback loop to see force exerted from the finger to the sensor. This idea has a lot more real-world application and with the ability to have both smart materials combined into one project it was too good of an idea to pass up.

Now that the team had figured out what to build, we started trying to figure out what the design might look like and originally, we start with the following cad model. This model was a real quick rough idea at to what we could make. Originally, we were planning on having two SMA wires that would move the figure but as we started working on the project, we found this idea to be a little too complicated. It was ultimately decided that we would use one SMA wire that loops around the finger to get better control. From there we also decided to use acrylic as a housing and therefore reworked the design into a more refined design with an acrylic box and dial indicator and room for the electronical components.

Even after these improvements there were some issues with the SMA wire being exploded to the wind and therefore we changed the design to the final iteration below. After we stared to assembly the device, we realized there was no place to put the electronics and therefore add some additional space, but at this

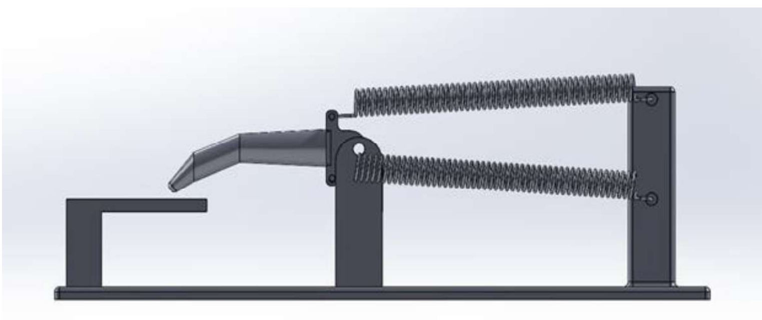

Figure 1: Original CAD Design

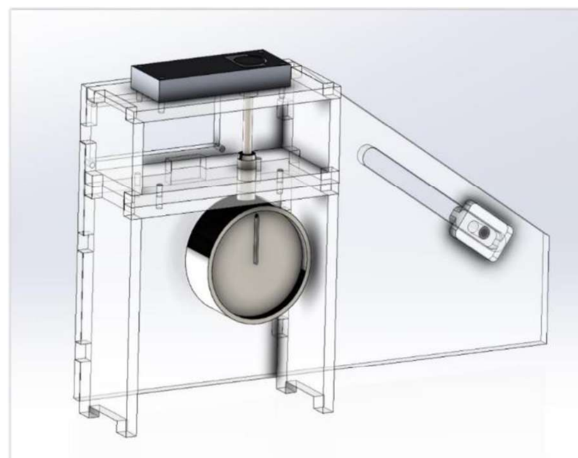

Figure 2: Second iteration of CAD

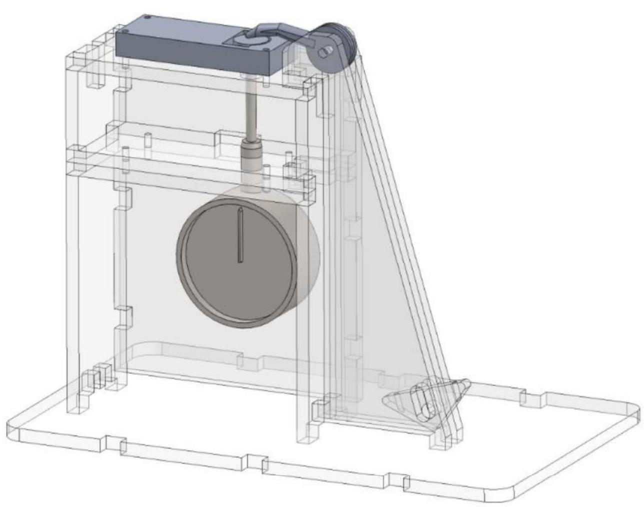

Figure 2a: Final design of upper catapult

Figure 2b: Finger design

point there were no other major improvements. Due to the changes being made on the fly we never updated the CAD to reflect the final design and therefore below is a picture of the finally assembly.

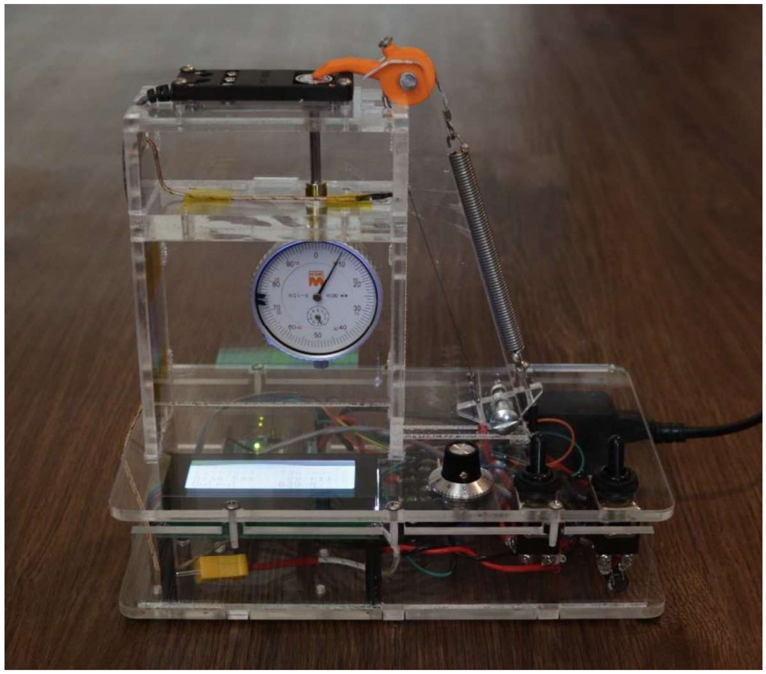

Figure 2c: Final Design

Electrical design

Since the system was intended to be actively controlled a microprocessor was needed as well as sensing and driving circuits. Additionally, it was desired to have the ability to easily change the setpoint and change the states of the system. To finalize the system as a whole an LCD screen was desired as well so that the values would be easy to see and record. A basic flow chard of the electrical and mechanical system is shown in figure 3.

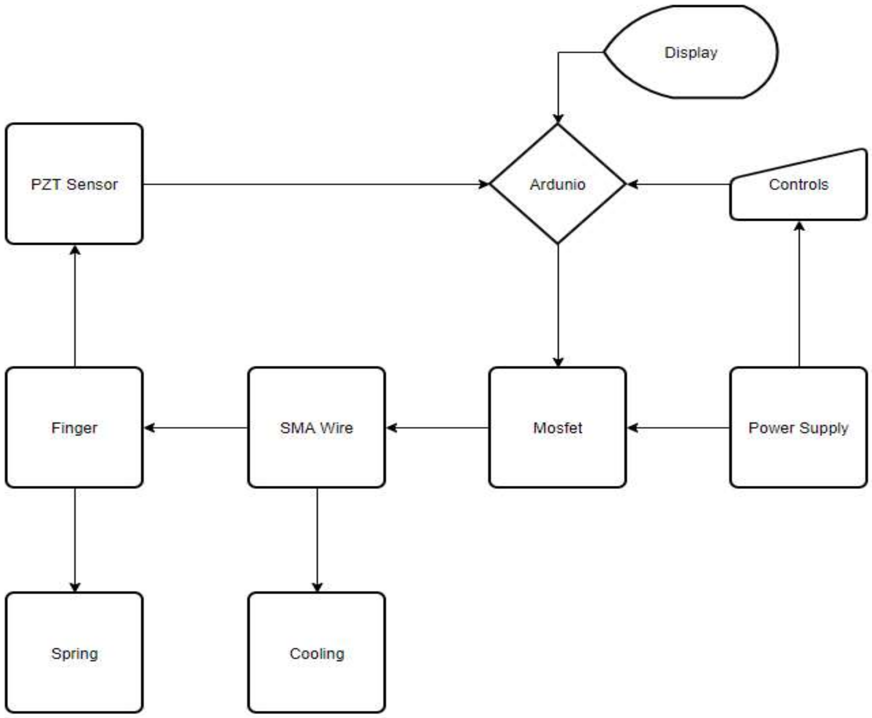

Figure 3: Electrical and Mechanical flow chart

The wiring was tedious, but not difficult, the mosfet used was capable of accepting logic level input so it was connected directly to one of the PWM pins of the Arduino with a 10K isolation resistor to protect the Arduino in case the mosfet should fail. The controls rely on a few 5V pull-down circuits that also utilize 10K isolation resistors protect the microcontroller. The power supply operates at 12V and has much more capacity than our system needs. The cooling in the chart is purely illustrative as our system is entirely passively cooled. Our display was generously lent to us by Dr. Willy and we extend thank to him. It utilizes a I2C bus which requires many fewer wires than other displays. Our program is based on elements from dozens of example sketches and from my previous experience with the platform. The sketch used in our final project is attached at the end of this report.

Modeling

A key aspect of our design was to include a dial indicator that would reference the deflection of the PZT sensor. This addition was of great benefit because it allowed us to verify that the sensor output was accurate. The modeling of the system was broken up into three parts: first, the modeling of the piezoelectric sensor and dial indicator; second, the modeling of the system compliance; and third, the modeling of the SMA wire actuator.

First, a series of measurements was carried out by placing known masses on the sensor and measuring the sensor deflection, and voltage output simultaneously. The voltage output was displayed on the LCD display of the system, and the deflection was given by the dial indicator (see figures 4 and 5).

Figure 4 LCD display of Arduino Microcontroller

Figure 5 Dial indicator

The data was entered into Excel and graphed (see figure 6). The graph of deflection as a function of force had a good linear fit and the slope represents the inverse stiffness of the sensor. This is true in spite of the

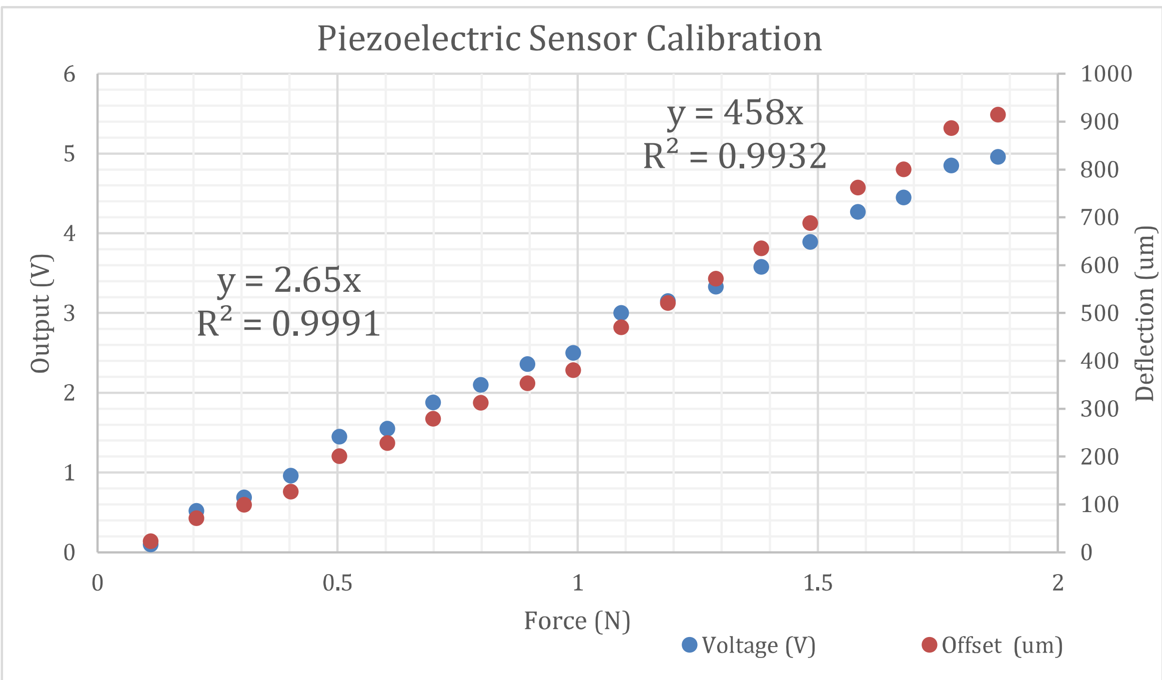

Figure 6

small spring force (284mN constant over our range of deflection) exerted by the dial indicator because the sensor is zeroed after having been deflected by the dial. The manufacture of our part (Piezo) did not furnish us with a spring constant directly, but did provide values for blocked force and free deflection ($0.54N\ and \pm 270\ \mu m$), and the slope of that graph is the sensor stiffness. $k_p^E = \frac{f_{bl}}{\delta_0} = \frac{0.54N}{270\mu m} = 2000\frac{N}{m}$ The value we obtained for inverse of the stiffness is $458E^{-}6\left(\frac{m}{n}\right)$ which leads to a larger stiffness constant $(458E^{-}6)^{-1} = 2183\left(\frac{N}{m}\right)$. Now the short circuit stiffness is a function of the elastic constant $Y_{11}^E\ since\ k_p^E = \frac{Y_{11}^E w_p t_p^3}{4L_p^3}$, but in our case we have an open circuit.

A correction can be made by multiplying the ratio of $\frac{Y_{11}^D}{Y_{11}^E}$ by the stiffness calculated earlier. Both of these values are also given by the manufacture and the result is as follows: $\frac{Y_{11}^D}{Y_{11}^E} = 1.13 \quad k_p^E * 1.13 = 2260\frac{N}{m}$ This value is only 3% larger than our calculated stiffness. It should be noted that the stiffness of the sensor is not wholly a product of the PZT characteristics since the sensor is not an ideal bimorph, however given the magnitude of the error here a recalculation of the sensor stiffness is not merited.

The graph of output voltage as a function of force shows a very linear response from the system and the slope represents the combination of the system stiffness and the electrical characteristics of the PZT. Since the manufacturer provided the blocked force and rated voltage for the sensor modeling was accomplished by taking the value for the blocked force and dividing it by the rated voltage, this gives us blocked force as a function of voltage. $\frac{f_{bl@Rated}}{V_{Rated}} = \frac{f_{bl}}{V_{Applied}} \quad \rightarrow \quad f_{Applied} * \frac{V_{Rated}}{f_{bl@Rated}} = V_{Generated}$ Note that if polarity was being kept track of $V_{Generated}$ would be negative with respect to $V_{Applied}$, however in our case we are not so much concerned with polarity as much as magnitude. Also note that our system includes a capacitor that is coupled with the sensor in parallel. This effectively reduces the voltage output of the sensor as: $V = q/C$, so $V_2 = \frac{C_1 V_1}{C_2}$, $C_2 = C_1 + C_{ext}$ This have a twofold benefit in that it conditions the voltage output to match the input requirements of the Arduino ADC, and it enhances the stability of the signal since the capacitor drain time is extended proportionally to the reduction in voltage. The generated voltage was calculated and compared with our measurements and the fit was good. There is some divergence at higher values but it is within reason since the deflection of the sensor is fairly large at those values (see figure 7).

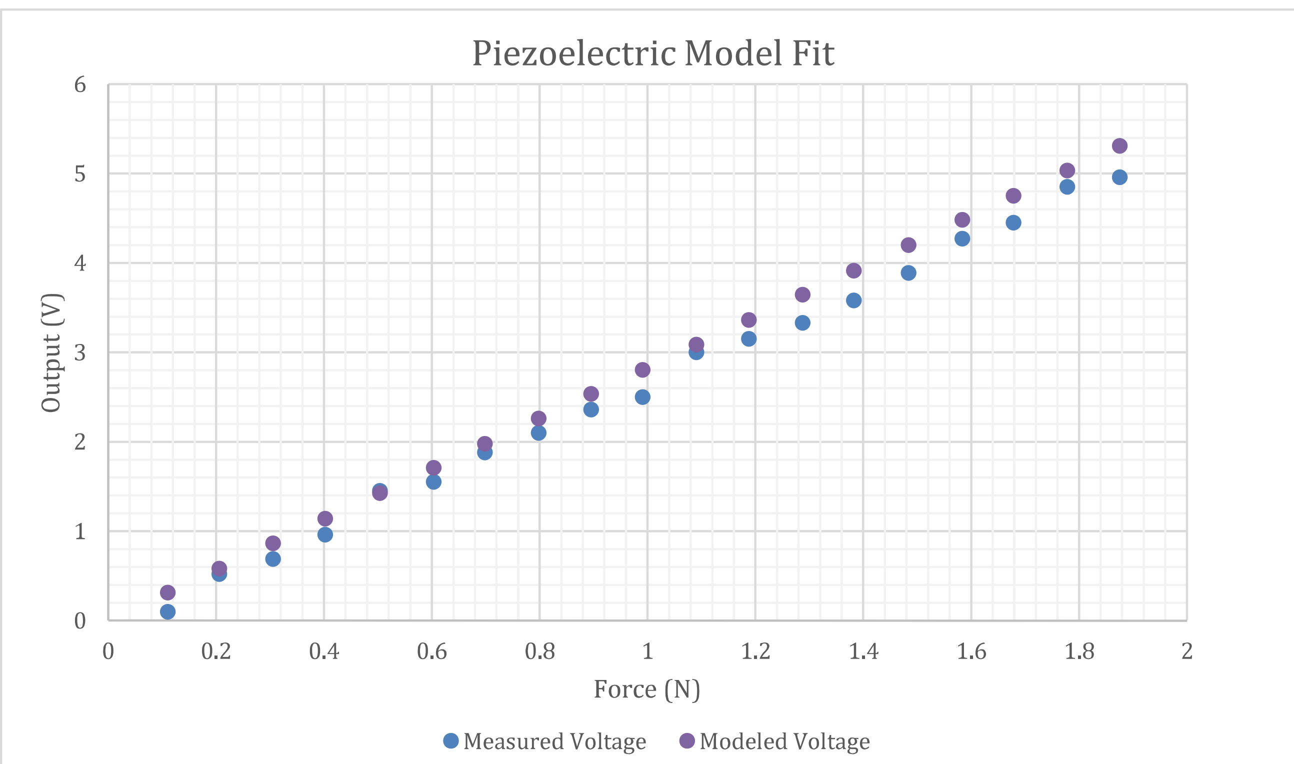

Figure 7

Having obtained the SMA modeling the next step was to model the mechanical aspects of the finger and spring. Early on the plan was to use the spring constant and sum up all of the forces that counteract the motion of the finger and the contraction of the wire. Because our system has so little movement in the spring it became impossible to adequately use it since the bulk of the forces were being generated by the assembly as a whole complying to our load. A method to characterize the system compliance was devised. and is shown in figure 8.

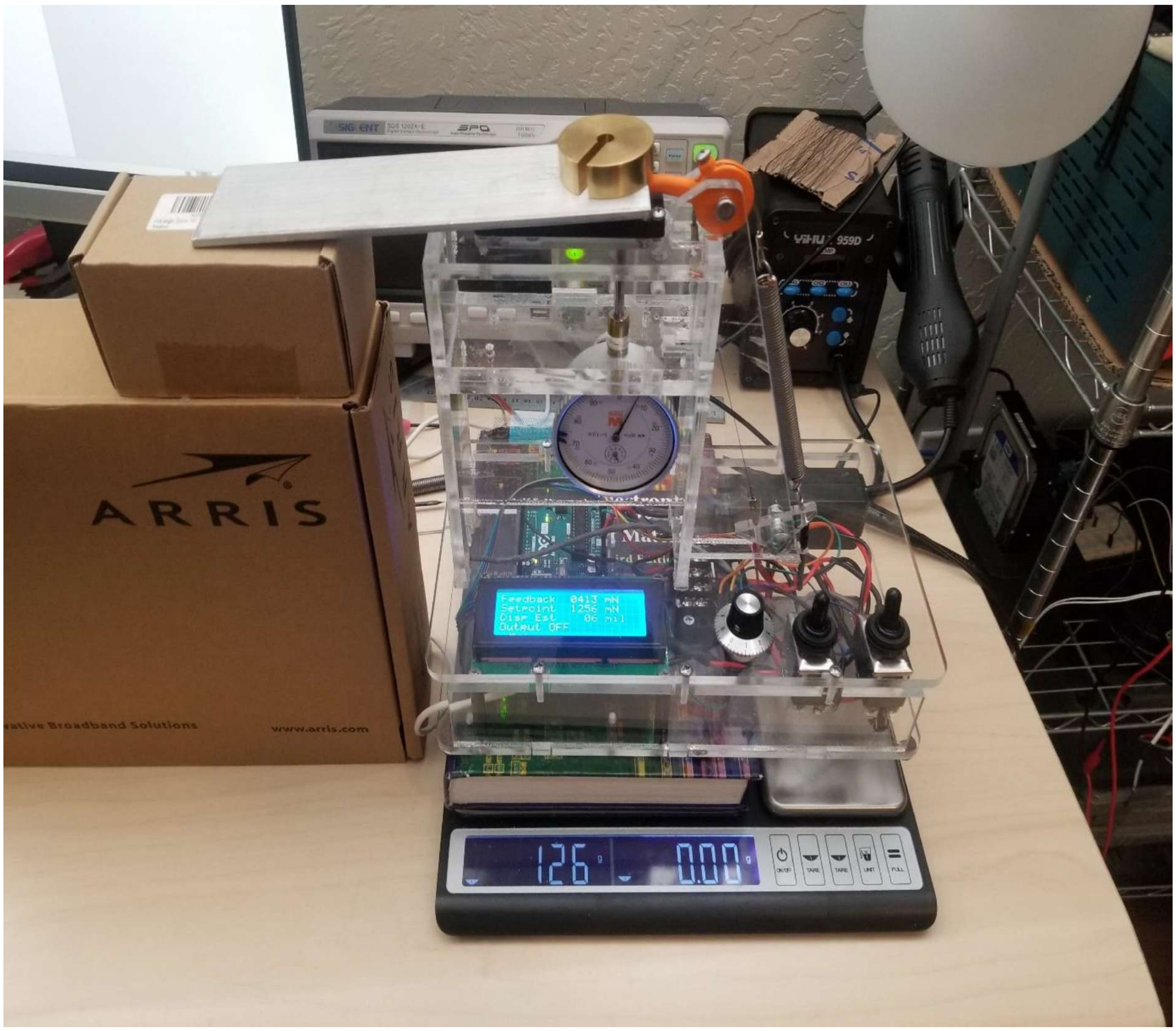

Figure 8: Method for characterizing compliance of the finger system as a whole

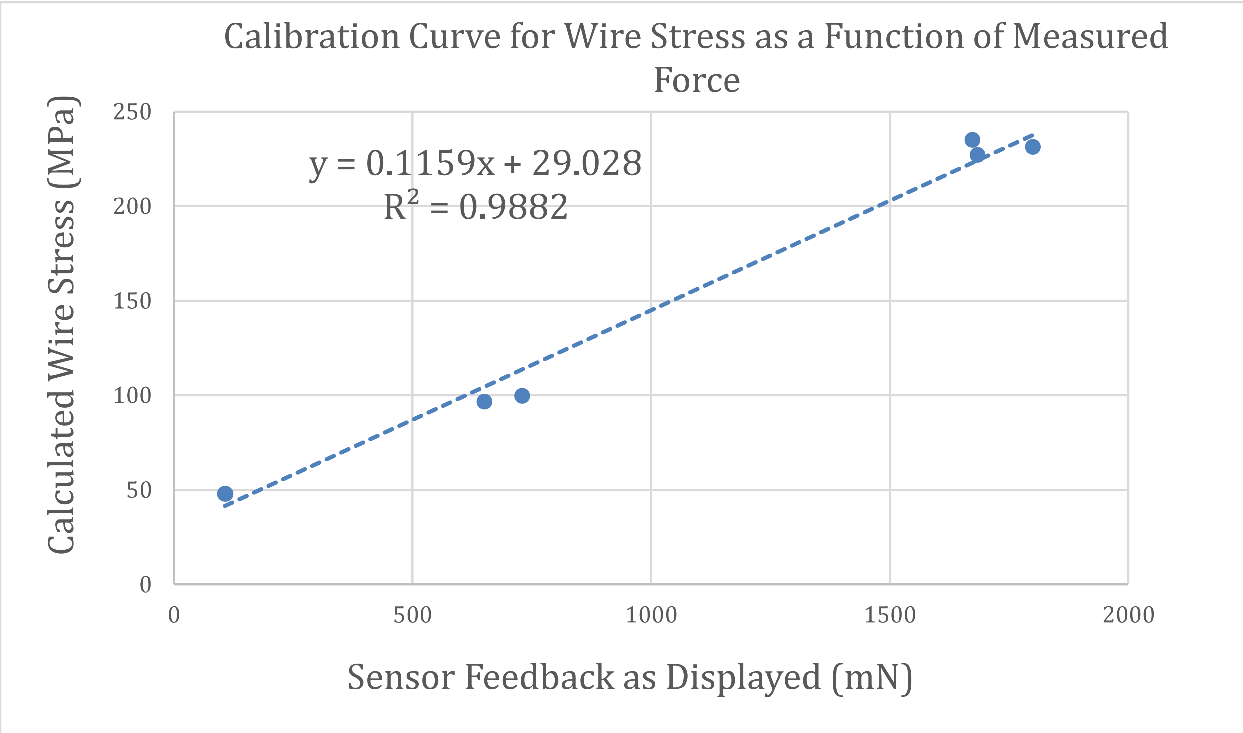

Figure 9

The entire system was placed on a scale, a line was drawn on the finger and the distance from the pivot joint to the mark was measured. The scale was zeroed and the aluminum bar was laid on the finger so that its edge was incident to the line, and masses of various sized were placed on the bar. These values were then graphed and analyzed (see figure 9). To calculate the wire, stress the length from the joint to the finger was divided by the radius of the pully that is acted upon by the SMA wire. Throughout the process the SMA wire was loose and did not contribute to the downward forces on the finger. Applicable conversion was made to change the measured mass to force and this was divided by the cross-sectional area of the 10-mil diameter SMA wire.

Now that the compliance of the system was known calculating the stress in the wire was easily accomplished and a thermal analysis needed to be done to determine the properties of the SMA wire. Unfortunately, although the wire appears to perform well, obtaining specifications for it proved to be an impossible task, so instead we characterized it to obtain what we needed. Our first objective was to obtain the values of $A_s \; and \; C_A$. This was accomplished by setting a large weight on a scale and attaching it to a length of SMA wire. The wire was then fixed to a vertical rack so that it followed a path normal to the floor. A small K-type thermocouple wire was bent so the bead formed a sort of hook and was set so that it gently pulled against the SMA wire. The scale was zeroed and varying levels of current were applied to the wire for a period of 60 seconds and values for the displaced mass and the temperature of the wire were taken withing the last 10 seconds of each interval. These values were graphed and a linear fit was found. This was one of the more difficult things to characterize because the temperature of the wire is highly sensitive to drafts, and also because the thermocouple introduces considerable thermal mass at the point where it is placed. The slope of the graph is the value of C_A and its temperature intercept is the A_s temperature (see figure 10).

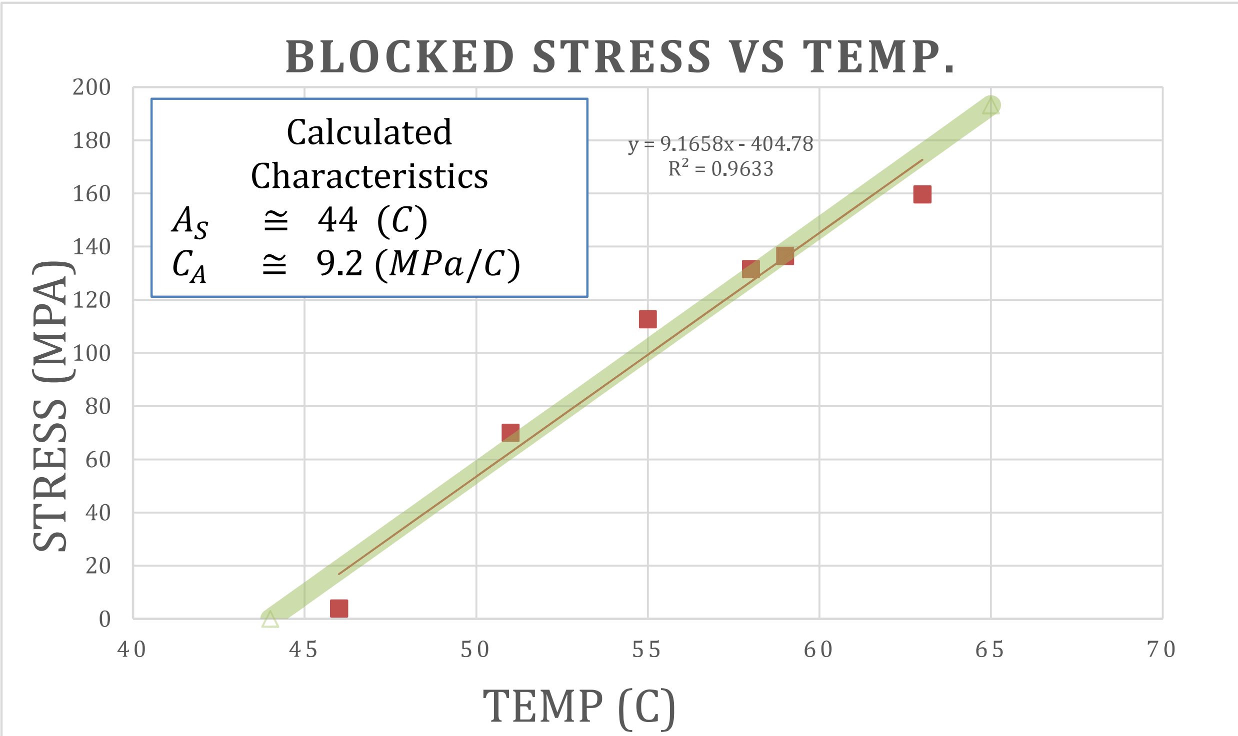

Figure 10: Characterization of SMA wire

Our next objective was to determine the heat transfer coefficient of our wire, this was done in a similar way to our characterization of blocked stress vs temperature, except that the current was monitored more closely and extra care was taken to avoid drafts. Once the data was obtained and graphed a calculated column was created that calculated the steady state temperature of the wire as a function of current. The formula is as follows: $T_{ss} = \frac{R}{h_c A_c} i^2 + T_\infty$ where T_∞ is the ambient temperature. R is the resistance per unit length (Ω/m) , A_c is the surface area per unit length $(m^\wedge 2/m)$ and h_c is the heat transfer coefficient $\left(\frac{J}{m^2\ C\ seconds}\right)$. All of these values excepting the heat transfer coefficient were calculated and a value for the heat transfer coefficient was obtained that provided a good fit for our data (see fig 11).

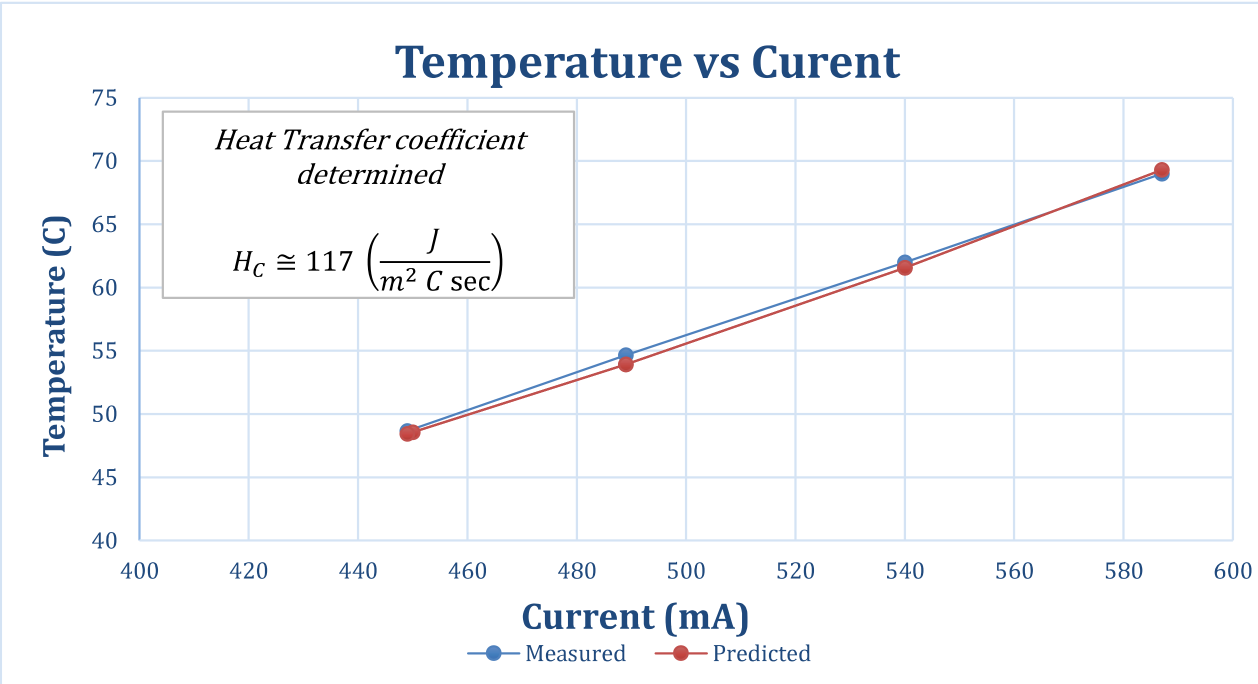

Figure 11: Determination of heat transfer coefficient

At this point all of the necessary material properties had been obtained for the modeling of the SMA wire. A combination of the equations for the stress dependance of the Austenite start temperature on stress and the steady state temperature dependance on current was used: $\sigma_{ss} = C_A\left(\left(\frac{R}{h_c A_c}\right) i^2 + T_\infty - A_s\right)$.

This formula was used in a calculated column and compared with data obtained from our system using a benchtop power supply to apply a constant current to the wire (see figure 12).

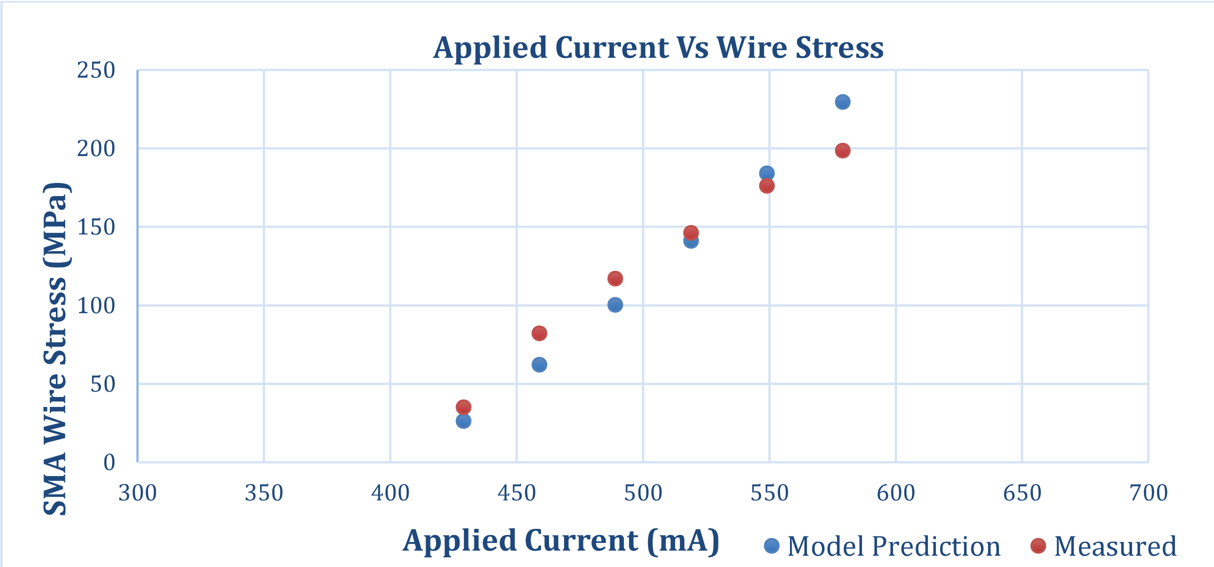

Figure 12

As a whole the system follows the expected behavior. And regardless of our modeling the PID parameters of the microcontroller have been optimized to quickly and accurately obtain a force valued and maintain that force steadily. The PID program was optimized using the standard method of varying the P first to obtain a value relatively close to the setpoint without substantial oscillations, then finding the smallest stable value of I and setting D to 1/6 of I. After doing this the system was able to achieve stability very quickly.

System characteristics

The system works as the team expected and through a few iterations of adding and taking away parts the device works the way the team intended. The device heats up the SMA wire which causes the wire to shrink which than exerted that force to the sensor through the finger. Underneath the finger is the PZT which allowed the team to get the applied force from the finger in the form of a voltage.

The SMA wire was used as a means, to apply force to the PZT. In our application this wire is contracting based on the joule heating provided to the wire. This provides a stress in the wire which makes it contract. The system is set up with a spring to make sure that any extra play in the wire is reduced. Due to the design, we are not using the SMA wire as a actuator therefore it is not pushing the finger up only expanding back to its original length and the spring resets the finger to the original position to than add more heat to the wire to cause it to shrink again. In the image below you can see how the finger has the SMA wire wrapped around the cylindrical part which then connects to the spring.

The other aspect of our system is the PZT which takes the force that is exerted by the finger pushing down on the sensor and converts it to an electrical signal. This is a crucial part of our design as we are using a

PID controller which makes sure that when we set a voltage value to the wire that we actually are seeing the correct voltage to the wire which give us the displacement we want for that voltage. The way the PZT was used was to make sure that we were getting the results that we were looking for. Due to the output of the PZT being an electrical signal, the team wanted an analog way to see what is going on. For the analog read out we got a dial indicator to validate the force and deflection coming from finger.

Lesson learned

Now that the device works, and all is well the team has found that there are discrepancies from what the book presents to what the manufacture gives you with regards to data. For example, the SMA wire came from McMaster-Carr and while the wire is nitinol, we have no idea what the performance of this wire actually is. This isn't an issue with regards to the application of device or the function of the device, but it made it challenging when modeling the data.

Another lesson learned is that SMA wire is very sensitive to ambient conditions. This was discovered when testing the wire and a breeze form an open door cause the wire to cool and give inconstant results for the tests that were being performed. This was one of the reasons the SMA wire is now in-between two sheets of acrylic to limit external effects on the wire.

We also learned a lot about the PZT how to get a signal out of it. In theory it is easy to think that you bend it and you get a voltage but how do you make a circuit that allows you to visualize this signal or for that matter use the signal for the loop? This was one issue the team faced but after a few different circuit configurations we found that using a simple parallel capacitor with the sensor acts as a voltage divider and in turn multiplies the available charge for measurement. The benefits of this were crucial to our measurement circuit.

Peer evaluation

The work present in this document is in no doubt due to Blake's ingenious ideas and his knowledge of not only these types of materials as well as his years of experience. The bottom line is he has had a few more years of experience on the electrical parts as well as the material science that backed this project up. Even his knowledge of the laser cutter which he helps reset up, after it got out of alignment. There is now way Ryan can compete with his knowledge or his expertise. Not only has Blake complete his master's but he is also worked in industry design systems with PID controls. His knowledge and abilities are not comparable to Ryan's. Due to this Blake spear headed a lot of this project and thankfully he kept Ryan in the loop enough to help and do his best to contribute. Ryan worked more on the documentation while Blake worked more on the modeling and setting the device up. Luckily Blake had more time to devote to this project which undoubtably allowed us to create the device outlined in this paper. Without his extra free time Ryan does not believe that this project would have been completed nor would it have been executed to this level of professionalism.

Conclusion

In conclusion, this project was a good way to apply what we learned in class to a real-life system. We gained a better respect for the equations from the book as we learned how to adapt with the discrepancies of real-world conditions that the equations do not take in account. All in all, the project was fun and exciting and we are very pleased by how well it works.