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Mechanical Testing of Artificial Muscles

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WWU PLASTICS ENGINEERING TECHNOLOGY

Mechanical Testing of Artificial Muscles

Senior Project Implementation 2014

Maggie Walsh

5/27/2014

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ABSTRACT

This document focuses on the design and fabrication of a low cost instrument to measure the strain of the artificial muscles being researched and developed by Dr. Amanda Murphy and her team at Western Washington University. The instrument utilizes a laser displacement meter to measure the movement of the artificial muscles during actuation. All project objectives and goals were successfully met, and all deliverables completed. Instrument quality and strain testing results are analyzed and recommendations for future work are suggested based on the results of the project.

INTRODUCTION

Overview

Dr. Amanda Murphy and her team at Western Washington University are currently developing biocompatible electromechanical actuators for use as biomedical devices [1]. These actuators are composite materials composed of conducting polymers, such as poly(pyrrole) (PPy), and silk [1]. Conducting polymers are electroactive polymers that have the ability to “undergo volume changes due to ion/solvent diffusion in and out of the polymer matrix upon electrochemical switching between oxidized and reduced states” [1 pg.2]. This means that these composite materials will expand and contract upon exposure to low operating voltages, making them capable of biomimetic movements [1]. The actuators developed and tested thus far at WWU contract and bend during oxidation "due to anion incorporation in the polymer matrix" [1 pg.16]. Relaxation of the polymer film occurs when the anions are expelled from the matrix during reduction [1].

In order to fully understand the potential of these actuators as biomedical devices, various forms of testing must be conducted and analyzed to see how they perform [2,3]. Prior to this project, Dr. Murphy and her team were able to gather data on the angle of deflection and force generated by these materials during actuation [1]. The process of actuation involves applying potentials to the material resulting in the material expanding and contracting [1]. To test and record the angle of deflection over time, films (of the material) were secured at only one end while potentials were applied, allowing for free-end bending [1]. In order to test the force generated by the film during actuation, it was secured at both ends while hooked up to a force transducer [1]. Potential was applied just as it was for the free-end bending to induce actuation [1]. The films were loaded with approximately 0.2 N of force in order to tighten them and stress was recorded over time [1]. Both tests saw similar behavior in the films with them contracting and stiffening during oxidation and relaxing during reduction [1].

The results of both studies aided Dr. Murphy and her team in demonstrating that these PPy and silk composites are capable of functioning as electromechanical actuators [1], however a method and device to measure strain during actuation is also of high importance in order to fully understand and evaluate these films as artificial muscles [2,3].

Problem Statement

Dr. Amanda Murphy and her team have developed biocompatible composite materials to be used as artificial muscles, but are in need of a low cost, instrument to test the strain of these materials during actuation.

Objectives/Functions/Constraints

- The artificial muscles need to be submerged in a liquid solution of phosphate buffered saline (PBS) during strain testing [1,2,3]
- The instrument must consist of a mechanism to measure strain of the artificial muscles during actuation

- If instrument utilizes a laser displacement meter, an object must be connected to the actuator that the laser can reference to make measurements
- The strain measuring mechanism must be able to sense minimal changes in position (strains of ~1-5% are expected for these materials [1-3])
 - Films are ~10mm in length [1], therefore measuring/detection mechanism must be able to detect minimal changes in position as small as 0.1mm
 - Therefore accuracy of the measurement mechanism should fall in the range of 10-1 um [2,6,12]
- The instrument must consist of a mechanism for restricting actuation motion to one axis (vertical or horizontal depending on setup)
 - If a load is used to meet this objective, the load should distribute evenly and be able to apply ± 0.2 N of force [1]
- The instrument must consist of a transparent cell or bath large enough to house the artificial muscle, necessary electrodes, and electrolyte solution (actuators are approximately 10x3mm and 0.05 mm thick)
- Cell/bath must be watertight
 - Airtight cap should be used if there is a pinhole in order to prevent dripping [5]
- The instrument must consist of a mechanism that can secure both ends of the artificial muscle within the cell/bath without interfering with the actuation process
- The potentiostat available for use for this project allows for two electrode hookups, limiting the project to the use of a working electrode and counter electrode [2]
- The data should be collected on a computer or easily transferrable which will be dependent on the specific laser purchased
- Corrosive materials exposed to electrolyte solution should be eliminated
- To reduce cost, setup should utilize materials and equipment previously purchased and currently available to WWU. This includes:
 - 2 electrode potentiostat
 - Computer
 - Gold Foil
 - Kapton Tape
 - Wire
 - PBS Solution
 - Artificial Muscle Films
 - Polystyrene Sheet
 - Three Prong Clamps (x2)
 - Clamp Stand
- Cost of project should ideally be ~\$2700 or less* [2]
- Project should be completed by Tuesday May 27, 2014**

*Grant money acquired by Dr. Murphy to purchase laser displacement meter allowed for increase in budget

**Approved extension due to delay in arrival of laser displacement meter

Goal

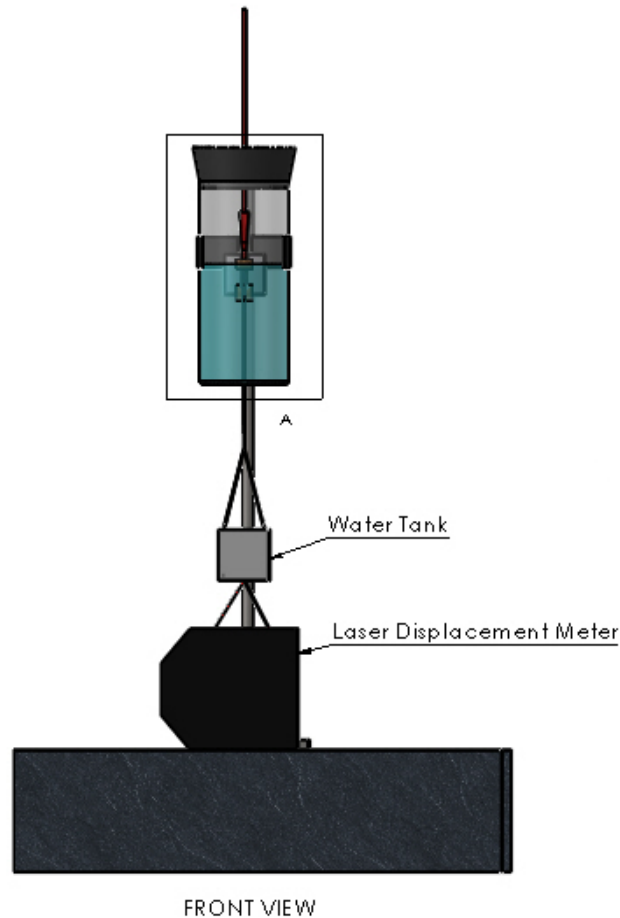
The primary goal of this project was to design and build an apparatus to measure the strain of the artificial muscles currently being developed by Dr. Amanda Murphy and her team at Western Washington University. The project should stay within the suggested budget, be completed by Tuesday

May 27th, and consistently provide good quality strain measurements [2]. The intended deliverables for this project included the purchasing of equipment, design and fabrication of the instrument, and development of a standard operating procedure for setup and testing with the instrument [2].

PROPOSED SOLUTION

The proposed design for the strain testing instrument was based off extensive research conducted during the proposal phase of the project. The design uses a transparent plastic submersion container filled with an electrolyte solution that houses both the actuator strip and a platinum mesh counter electrode. The actuator strip is secured at both ends using kapton tape. Gold foil is used to make electrical contact between the working electrode and the top end of the actuator. The bottom end of the actuator is attached to fishing line that will pass through a pinhole in the base of the container and connect to a water tank. To prevent the electrolyte solution from leaking through the pinhole, a rubber stopper is used to cap the container and create a vacuum inside. The hanging tank is filled with water, pulling the actuator taut and restricting movement to the vertical axis. The tank also functions as the reference for the laser displacement meter since its movements up and down reflect the movements of the artificial muscle during actuation.

The plastic container is clamped in a three prong clamp attached to a clamp stand. The laser displacement meter is positioned directly below the cell and hanging water tank in order to measure the movement of the artificial muscle. Schematics of this proposed design can be seen below in Figures 1 and 2.



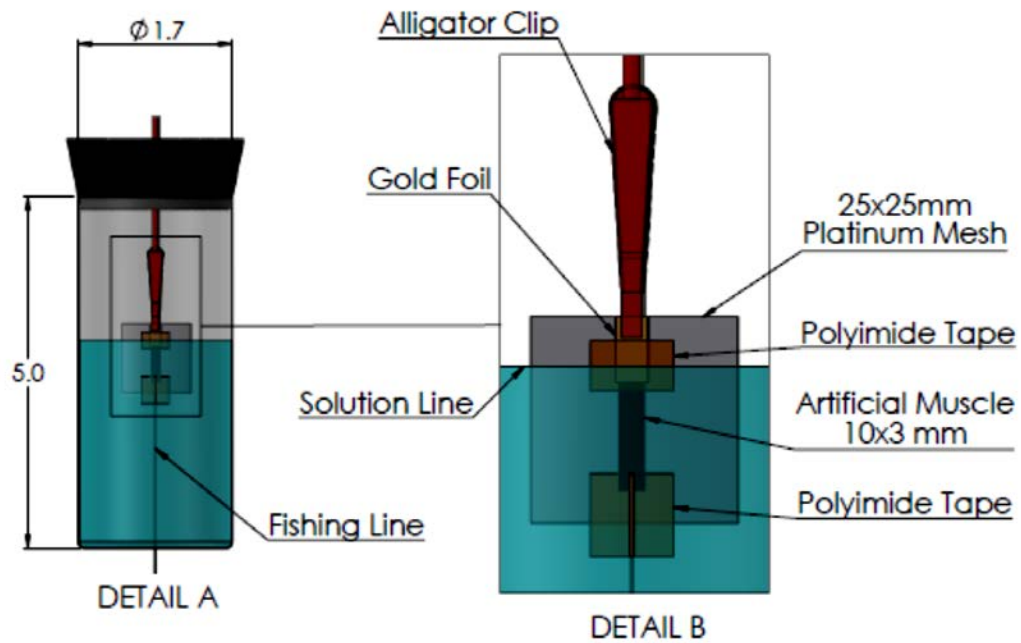


Figure 1: Front view of proposed solution design with close-up views of cell (Detail A) and artificial muscle assembly within cell (Detail B). Includes proposed minimum dimensions of cell and solution line.

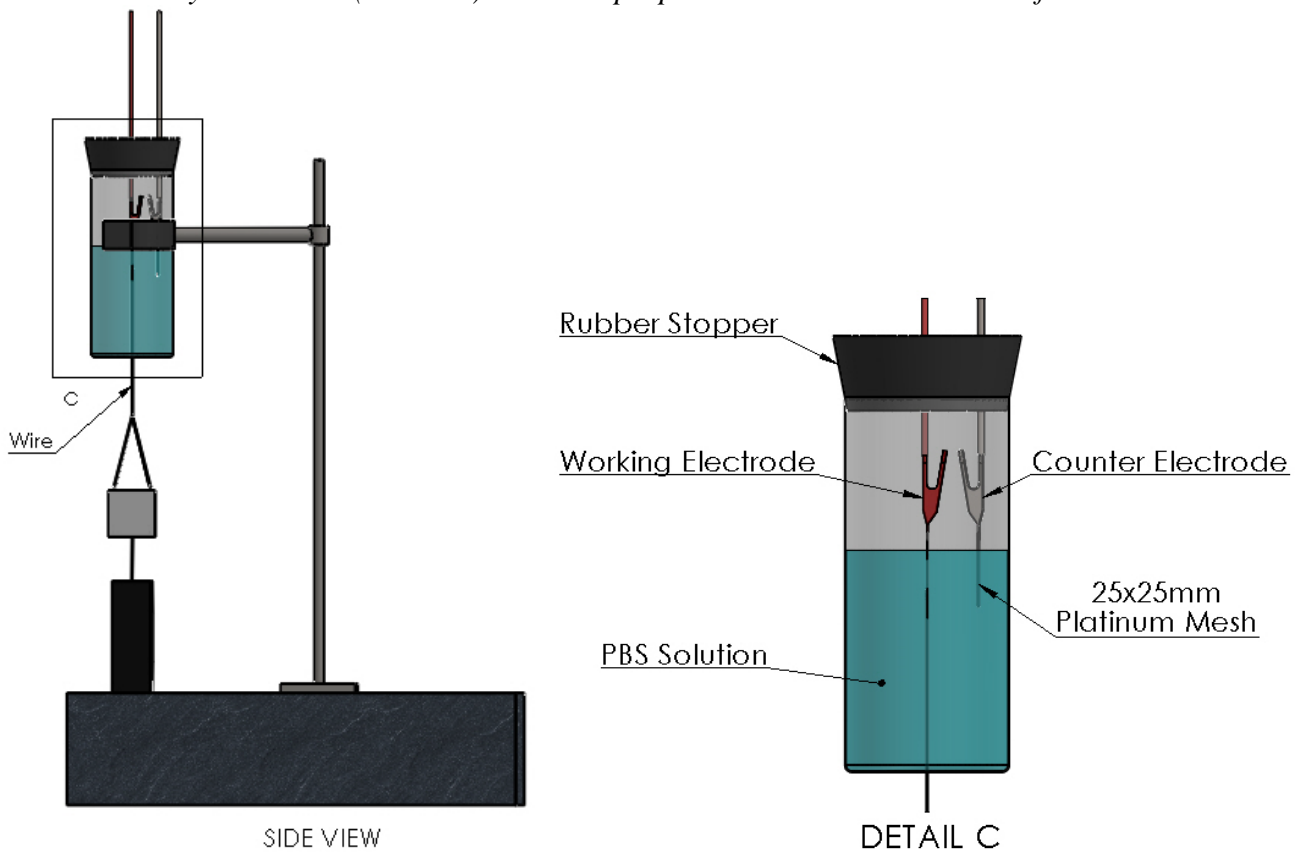


Figure 2: Side view of proposed solution design with close-up detail of cell (Detail C).

METHODOLOGY

The steps taken during the implementation of the project are listed and explained below in the order of completion.

1. Assessment of Demo Laser

Before making a final decision of which laser displacement meter to purchase, a demo of the Micro-Epsilon optoNCDT 1402 laser was sent by the manufacturer and assessed during finals week of fall quarter. Nathan Bradshaw, a member of Dr. Murphy's research group, conducted this assessment with my assistance. The laser was fairly simple to hook up, met accuracy requirements (measurements in mm to four decimal places), and came with a software program that was user friendly to measure, record, and export all the data. It was noted that a method of keeping the laser steady and secure would be important to reduce noise, and minor movements near the laser were detected due to its high sensitivity. This assessment verified that the laser would be a good fit and would meet the requirements for the instrument.

2. Purchasing of Equipment

The equipment purchased for the project included a transparent plastic jar to be used as the submersion container, a rubber stopper, fishing line, polystyrene cement, epoxy glue, and the laser displacement meter. Aside from the laser, all equipment was purchased during the first week of winter quarter, and arrived during the 2nd and 3rd weeks. In order to purchase the laser displacement meter, Dr. Murphy applied for a grant. For this reason, it was initially predicted that the laser would arrive by mid February. However, due to a delay in the order's progress through WWU's purchasing department, the laser did not arrive until the Friday March 14. This resulted in large deviations from the original timeline, which will be explained in more detail the timeline analysis portion of this paper.

3. Fabrication of Instrument

a. Plastic Submersion Container

The only modification needed for the plastic submersion container was a small hole drilled in the base. This was done using a manual drill from the PET soft tooling lab. The hole was drilled with a 7/64" drill bit, and burrs were removed with a razor blade.

b. Hanging Water Tank

The hanging water tank was constructed out of white polystyrene sheet stock. This was chosen because of its ability to be solvent welded, and a white surface is optimal for the laser to clearly detect. Five rectangular pieces of the plastic were first measured, then cut using the band saw located in the PET soft tooling lab, and finally sanded to remove burrs. Following this, the five pieces were solvent welded together using polystyrene cement, and left to dry overnight. Once dry, 2 thin pieces of metal were bent in a v-shape. These were attached with epoxy adhesive to opposite corners of the box, overlapping at the bend in the center. See image 1 below for visual understanding. A drawing showing dimensional details of the tank can be seen in Appendix C. To check if the tank was watertight, it was filled with water and left to sit on a paper towel for 15 minutes. The tank appeared to be watertight since there were no signs of liquid on the paper towel.

c. Rubber Stopper

The rubber stopper needed two holes drilled through it in order for electrode leads to pass through. The drill press in the PET soft tooling lab was used for this step. The first hole was drilled in the center of the rubber stopper with a 13/64" drill bit, and the second hole was drilled approximately 1/2" away from the center with a 1/8" drill bit (see Appendix B). The reason the second hole was smaller, was because after drilling the first hole, it was determined that it did not need to be that large for the electrode lead to pass through. Once

the holes were drilled, the rubber stopper was given to Nathan Bradshaw, so that he could feed the leads through and attach alligator clips. Once this was complete, the original plan was to glue these leads permanently in place. However after talking with Nathan, it was decided that it would be better if the leads were not permanently sealed and instead remained adjustable. After some brainstorming, it was decided that sealant tape would provide a non-permanent air-tight seal, allowing the leads to be adjusted if necessary. Two small pieces of sealant tape were used to seal the leads in place, and then tested for quality by adding water to the plastic container, capping with the rubber stopper and observing if liquid leak through the pinhole. Aside from the initial leakage of water through the pinhole as the pressure difference was attained, the container did not leak, confirming that the sealant tape would be a sufficient non-permanent alternative to glue.

4. Testing Vacuum Seal & Liquid Lost Through Pinhole

As mentioned previously, in order for liquid to not leak from the pinhole located at the base of the plastic submersion container, the container must be capped and air tight. A rubber stopper was chosen to fulfill this need, and proved to be a good choice. It was observed that once liquid was added to the submersion container and capped and thoroughly sealed with the rubber stopper, a small amount of liquid leaked out initially, but then ceased. Testing was done to see approximately how much liquid leaked out.

5. Initial Instrument Assembly without Actuator Strip

Once the submersion container, rubber stopper, and water tank were made, the components were assembled without an actuator strip. Wire was used to hang the water tank and was clipped to the working electrode alligator clip since a strip was not being used. The wire proved to be a poor fit for this application due to observed kinking and difficulty making it hang perfectly vertical. Some brainstorming was done to determine a better option. Fishing line was thought of as a potential replacement for the wire since it is thin, strong, and would likely hang vertically without kinking. Fishing line was purchased, tested, and proved to be a good fit. During these initial assemblies, it was determined that the setup would require two people to fill the container with the PBS solution and seal it with the rubber stopper. One person holds the container and plugs the pinhole with their finger, while the other adds the PBS solution and caps the container with the rubber stopper.

6. Strain Testing without Laser Displacement Meter

Three separate days of strain testing were conducted using the instrument minus the laser displacement meter. Jesse Larson and Nathan Bradshaw helped out with the instrument setup and ran the actuation. On the first day of these tests, a method of taping the strip to the gold foil and the fishing line was developed. Since the laser displacement meter was not yet delivered, a video camera was set up to attempt to capture actuation movement. It was focused in on the hanging water tank, and a white piece of paper with a horizontal black line drawn on it was placed behind for the purpose of measuring the distance between the base of the tank and the line. The video footage ended up not being useful since the movements of the actuator were so slight that they could not be identified in the footage. These initial strain tests were helpful in working out the best methods of setting up the instrument.

7. Setup and Configuration of Laser Displacement Meter

Due to the complicated setup and wiring of the laser displacement meter, this step of the project was completed by Nathan Bradshaw. Once this was done, the laser was ready to be incorporated into the rest of the assembly. The laser came with a software program that can measure, store, and export the displacement data into an excel file.

8. Instrument Assembly with Laser Displacement Meter

The laser displacement meter was the last component needed before the instrument was complete. The laser has a 5 mm measurement range that falls 20 mm away from it, meaning the laser can

detect an object positioned anywhere in the range of 20-25 mm away. Therefore, the laser needed to be positioned below the hanging water tank within that range. To do this, a lab jack, whose surface height can be easily and minutely adjusted with the turn of a knob, was positioned below the water tank for the laser to be secured on. Due to the laser's high sensitivity to any movement near it, it needed to be securely stabilized on the surface of the lab jack to reduce noise. A three ring clamp was attached to the clamp stand and clamped to the laser, keeping it stable and in place. To position the laser at the necessary height, the measurement software was utilized. It shows the laser's current distance when it is in the 5 mm range. The current distance displays a number from 0.0000 mm to 5.1000 mm which means the object is 20 mm plus the current distance reading away from the laser. Prior to knowing about the strips' tendency to creep throughout the actuation, the laser was initially positioned in the center of the 5 mm range. This was too low, and the strip elongated out of range, meaning data could no longer be collected for that test. To prevent this from happening again, the laser was positioned at the top of its range near 5 mm for all further tests. Data was never lost due to the strip elongating out of range after this adjustment in the setup procedure.

9. Strain Testing with Laser Displacement Meter

After the laser was incorporated into the instrument assembly, strain testing with data collection was conducted. Through these tests, it was determined that the instrument performed well and the laser had the resolution to detect the minor actuation movements. During the force generation testing, a creep phase prior to actuation was deemed necessary to allow the strip to relax and achieve a lower static stress. For that reason, a creep phase was implemented into the strain testing as well. The strain testing helped confirm the capability and quality of the instrument. It also identified the tendency of the strip to creep not only during the creep phase, but throughout the actuation as well. This characteristic was unknown prior to strain testing, and should be investigated with the use of the instrument.

10. Development and Writing of Operating Procedure

An operating procedure was developed over the course of strain testing. The method for setting up the instrument was largely based on trial and error, but also force generation testing methods. For example, since a creep phase was used in force generation testing it was also implemented into the strain testing. The best method of taping the actuator strip to the gold foil and fishing line, feeding the fishing line through the pinhole, and adding PBS solution to the container and capping with the rubber stopper were all developed through trial and error. As for setting up and operating the laser displacement meter, the instruction manual provided by the manufacturer Micro-Epsilon as well as instructions from Nathan Bradshaw were used. A draft procedure was edited by both Nathan Bradshaw and Jesse Larson, and a strain test was conducted following the steps in the procedure to identify any missing steps as well as the clarity of steps.

RESULTS

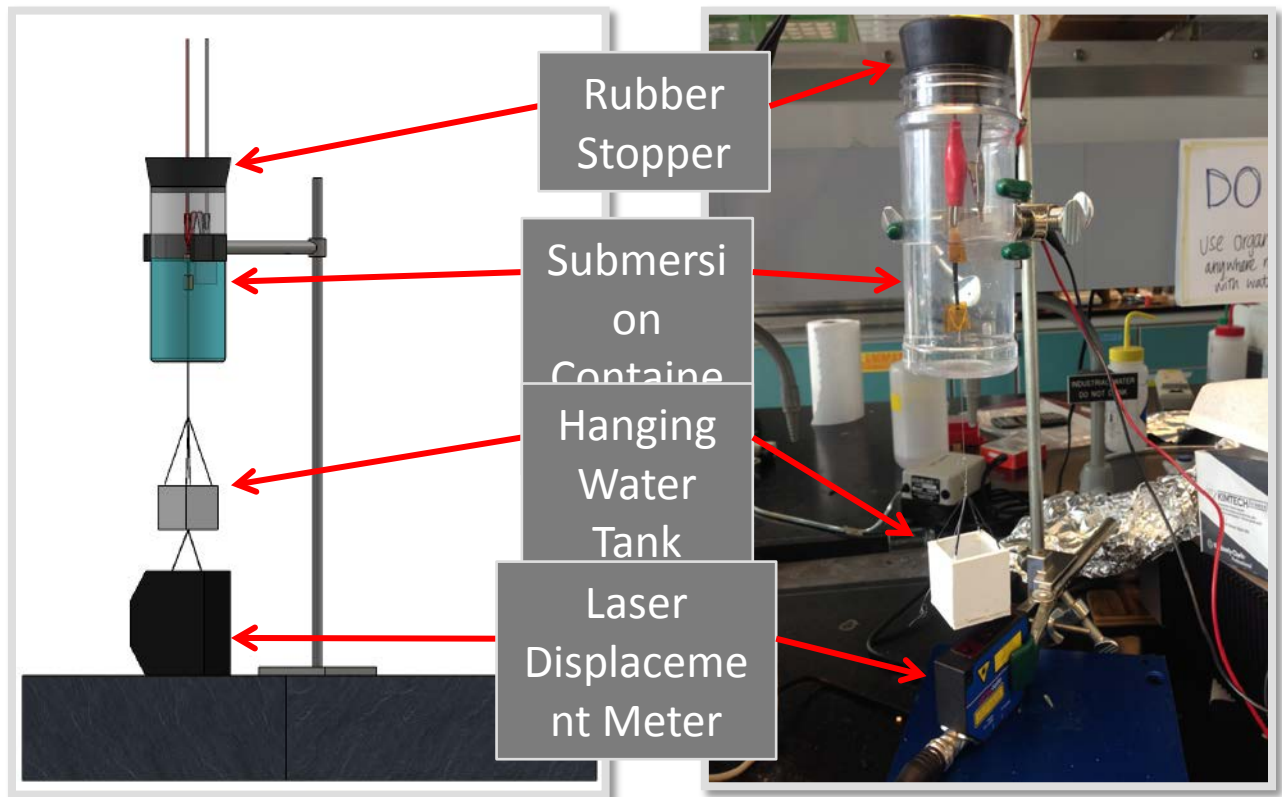


Figure 3: Proposed instrument design (left) compared to actual instrument (right)

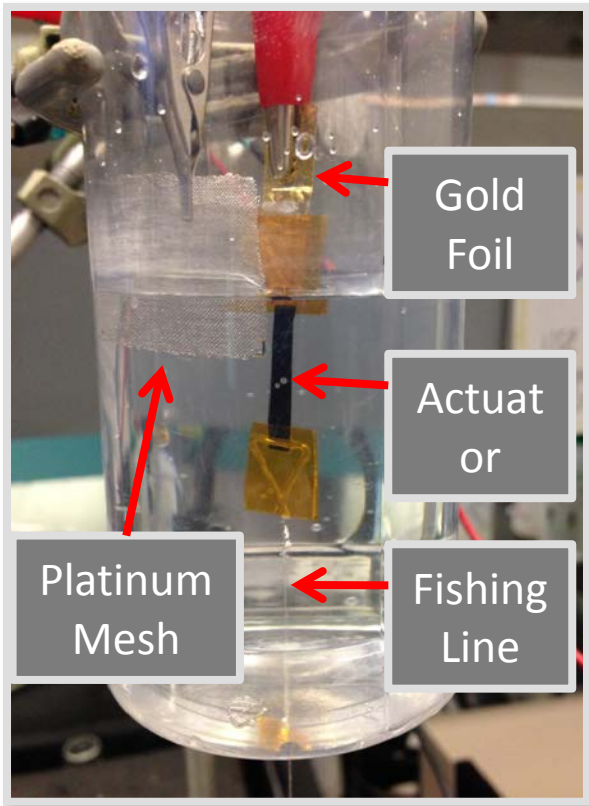


Figure 4: Close up of submersion container

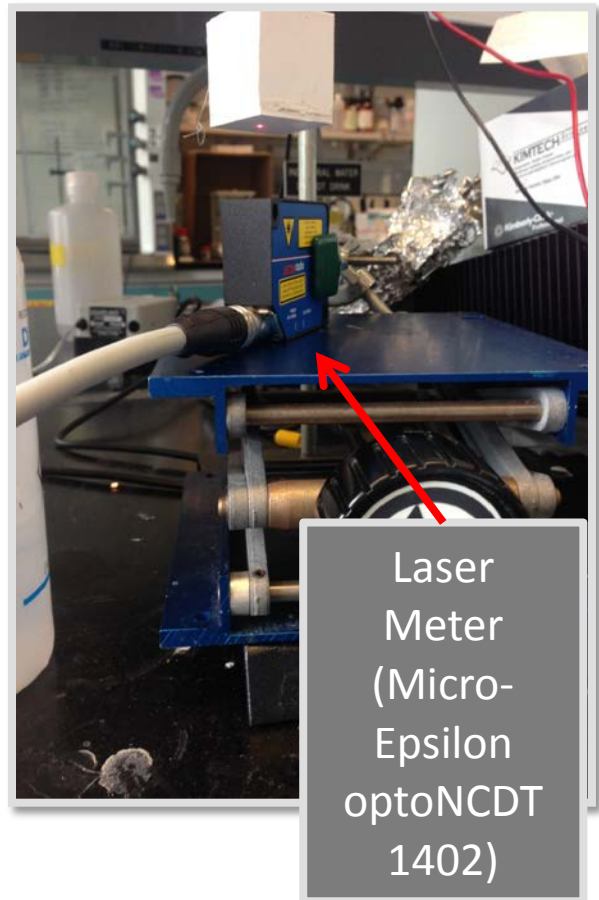


Figure 5: Close up of laser displacement meter positioned on lab jack and referencing water tank

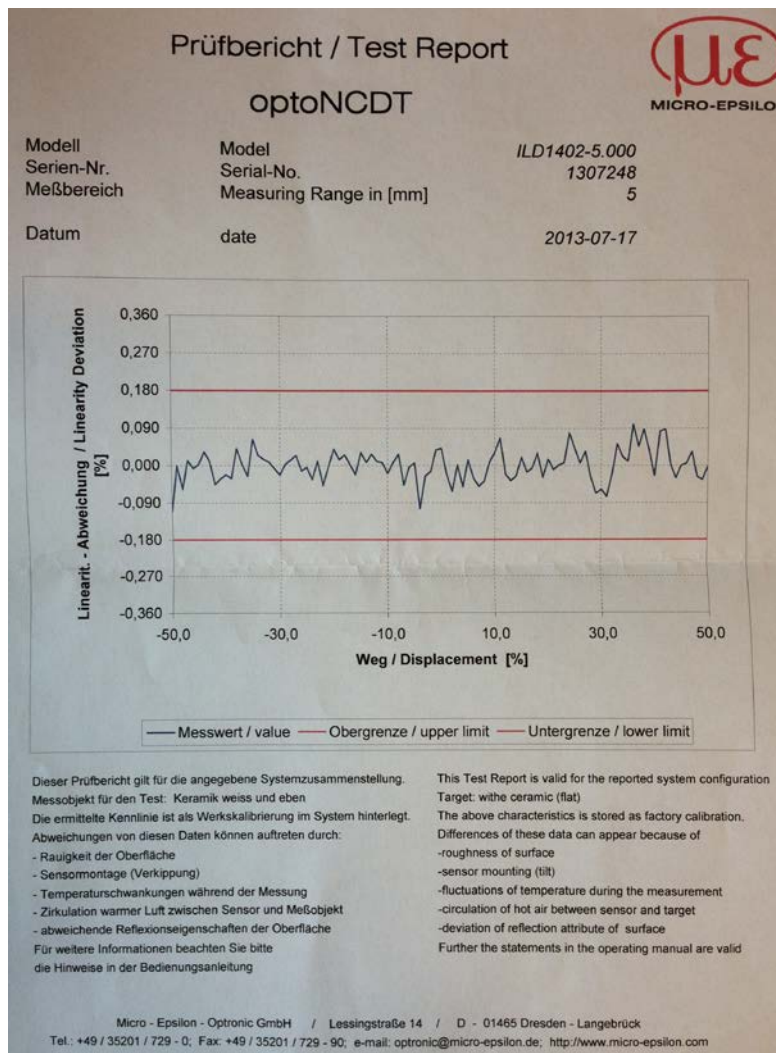


Figure 6: Control chart sent by Micro-Epsilon showing laser was calibrated and within linearity control limits of $\pm 0.180\%$

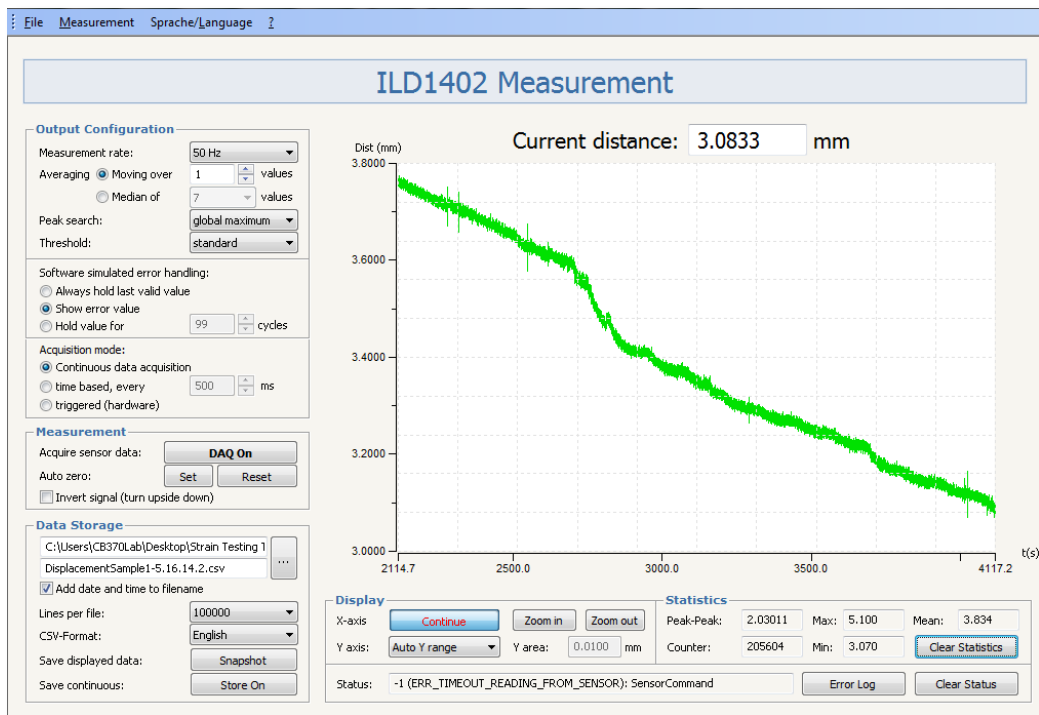


Figure 7: Screen shot of laser measurement software.

Table 1: Data from testing the amount of water that initially leaks from the plastic submersion container after it is capped with the rubber stopper. The right-most column shows the amount of water lost for each run, with the average and standard deviation calculated in the last two rows. Note: run 11 was removed because finger did not fully seal pinhole, causing excess water to leak.

Run	Water Added (g)	Empty Beaker (g)	Beaker + Water Remaining (g)	Water Remaining (g)	Water Lost (g)
1	100.072	109.102	201.412	92.310	7.762
2	99.912	109.014	203.322	94.308	5.604
3	100.074	108.962	203.903	94.941	5.133
4	99.945	109.012	201.284	92.272	7.673
5	100.020	109.263	204.076	94.813	5.207
6	70.081	109.015	172.981	63.966	6.115
7	89.961	109.047	192.488	83.441	6.520
8	98.921	109.022	202.293	93.271	5.650
9	100.570	109.062	203.804	94.742	5.828
10	54.407	109.031	157.247	48.217	6.190
12	113.558	51.810	160.378	108.567	4.991
13	114.047	51.809	161.177	109.368	4.679
14	71.860	51.911	117.627	65.716	6.144
15	87.052	51.892	131.949	80.057	6.995
16	93.295	51.898	139.303	87.405	5.890
				Average	6.025
				Std. Dev.	0.914

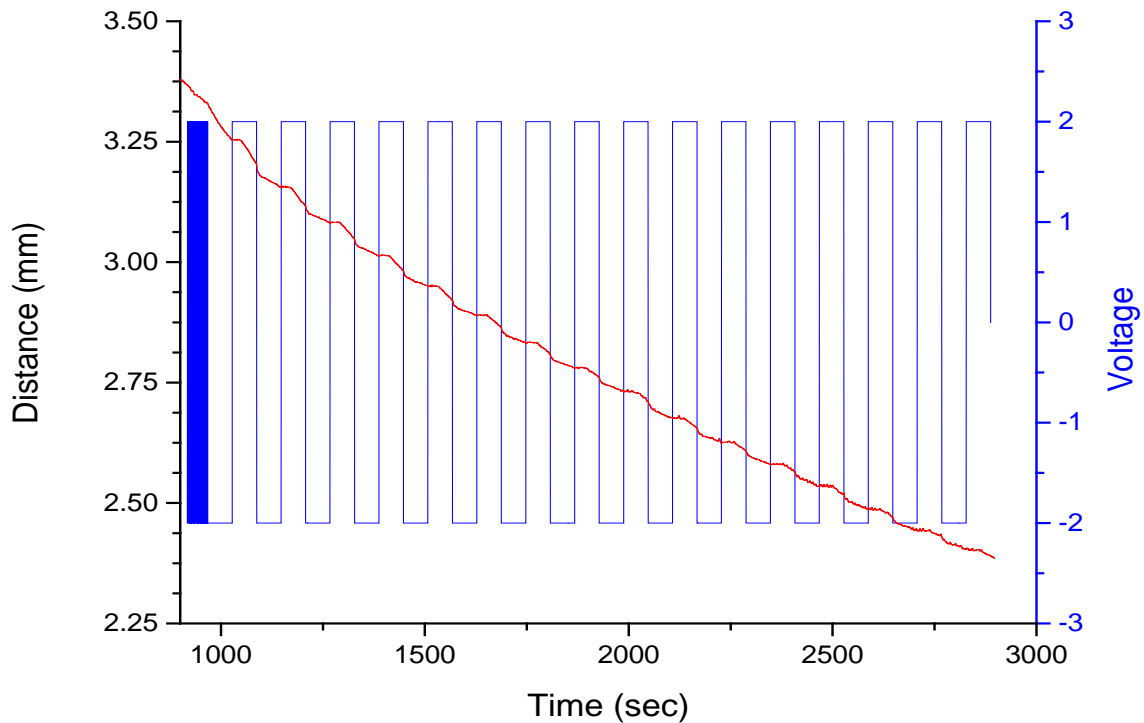


Figure 8: Distance (mm) and Voltage vs. Time (sec) graph from strain testing day 2 sample 3. Distance (in red) indicates the reading from the laser displacement meter during actuation (decrease in distance=elongation of actuator strip). Graph made by Nathan Bradshaw.

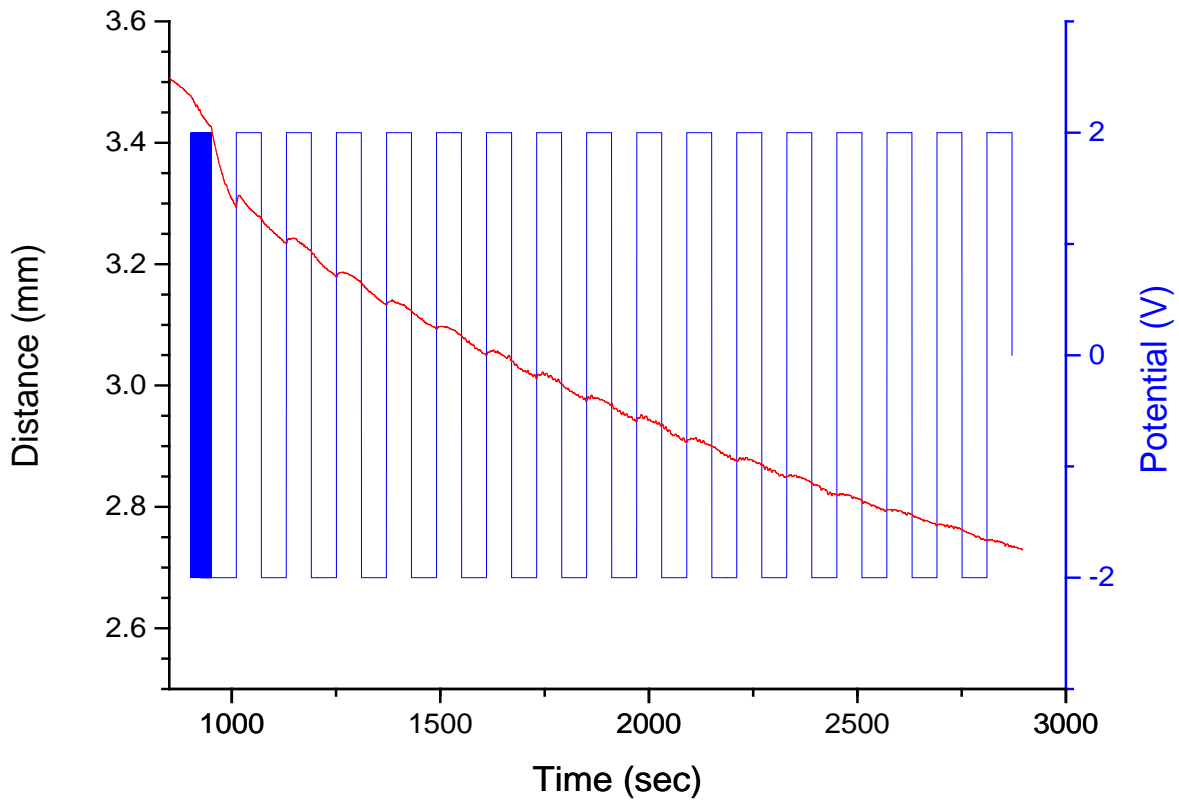


Figure 9: Distance (mm) and Potential (V) vs. Time (sec) graph from strain testing day 3 electropolymerized sample. Distance (in red) indicates the data from the laser displacement meter during actuation (decrease in distance=elongation of actuator strip). Graph made by Nathan Bradshaw.

ANALYSIS

Instrument Quality

A picture of the fully assembled strain testing instrument that was built for this project in comparison to the proposed design can be seen in Figure 3. As can be seen in these pictures, the instrument looks very similar to the design. Aside from a few minor modifications (to be explained), the proposed design was successful and functioned as expected. Figure 4 shows a close up view of the submersion container. The kapton tape successfully secured both ends of the actuator, the fishing line suspended the hanging water tank directly below the strip passing through the pinhole, and the rubber stopper provided an air tight seal to prevent the PBS solution from leaking through the pinhole. The electrode leads attached to alligator clips were adjustable thanks to the use of non-permanent sealant tape. This meant that the fill line of the PBS solution could be a general estimate instead of a precise height, and also allowed for varied lengths of strips and gold foil to be usable in this set up.

Figure 5 shows a close up view of the laser displacement meter secured on the surface of the lab jack and referencing the base of the hanging water tank. The hanging water tank weighed approximately 12 g, and with the addition of approximately 8 g of water, a load of approximately 0.2 N could be applied to the strip, similar to the force generation testing. The water tank would often swing a bit after being attached to the fishing line, and was stabilized by holding an object such as forceps or a clamp near it prior to data collection. The laser displacement meter, after adjusting the height of the lab jack in order for the laser to be at the top of its range, was securely clamped in place with a clamp attached to the stand holding the submersion container. This helped to improve the consistency of the measurements by preventing noise caused by movement near the laser. Utilizing the lab jack to adjust the height of the laser in respect to the water tank is much easier than securing the laser to the counter top and adjusting the height of the rest of the instrument.

Figure 6 is a picture of the control chart sent by Micro-Epsilon showing that the laser was calibrated and within linearity control limits. This means that the measurements the laser makes are highly accurate, within 0.180% of the actual value. Since the movements of the actuator strip are so minor, this accuracy is very important. The laser has an accuracy of 0.6 μm [12] which surpasses the requirement for a measurement system with an accuracy of 10-1 μm . This confidence in the measurement device would not have been as strong if a laser had been purchased used. Another great feature of the Micro-Epsilon laser displacement meter that was purchased for this project is the measurement software program that it came with. Figure 7 shows a screen shot of the software program. The software not only shows the laser's current measurement, but also collects the measurements, stores them, and can then export the measurements into an excel document. The graph shown on the screen in Figure 7 is the graph from an actuation, and all that data was also stored in an excel file and used to make the graph in Figure 9. In comparison, the graph in Figure 7 appears much noisier due to the vibration of the chemistry building. However, this vibration was fairly consistent, and excel's smooth curve function was used to create the less noisy graph seen in Figure 9.

Overall, all objectives, functions, and constraints relevant to the instrument itself were met. The laser displacement meter is calibrated with high resolution and accuracy, and all other components of the instrument function as intended. However, there are some drawbacks of the instrument, and while they don't have a large impact on the overall quality, they are important and should be taken into consideration. The first drawback is that the setup requires two people and takes practice to complete with ease. For example, it takes a few attempts to get used to working with the kapton tape and the process of taping the strip to the gold foil and fishing line. The next drawback of the instrument is that the laser detects any movement near it due to its high sensitivity, such as connecting the electrode leads from the potentiostat or bumping into the counter. Fortunately, the graph feature of the measurement software can be utilized to identify the time that any movement not related to the strip occurred in order

to ensure it is not mistaken for true data. The last drawback is the vibration in the chemistry lab which causes noise in the measurement data. However, as mentioned previously, this noise appears to be fairly consistent and the smooth curve function in excel can be used to remove it.

Testing: Solution Lost

When liquid is added to the submersion container and capped with the rubber stopper, an initial amount of liquid leaks out of the pinhole. The results of the testing done to see approximately how much liquid leaked out can be found in Table 1. An average of approximately 6 g of liquid was lost. This testing helped quantify the amount of solution that would likely be lost during the setup of the instrument, and was helpful in determining how much solution to add to the submersion container in order for the strip to be fully submerged without exposing the gold foil to the solution. During the first setup of the instrument, a solution line was drawn on the container based on the information from this testing, as well as seeing how far down the strip was located in the container when attached to the gold foil and clipped to the electrode lead. This solution line was used as a guideline for all strain testing, and proved to be a good estimate.

Testing: Actuations

Strain data for two different samples can be seen in Figures 8 and 9 which show the distance measurements recorded by the laser displacement meter overlapped with the applied voltage. The data collected from the strain testing showed that the movements of the actuator strips were consistent with what was expected. When positive voltage was applied, the strips contracted. This movement was indicated by either a positive or approximately zero slope on the distance graphs (see Figures 8 and 9) meaning the strips either shrunk, or stopped elongating for a moment. The strongest contractions were observed in the first couple cycles of actuation which is likely due to the fact that the measured current of the strip decreases throughout out the actuation as the strip degrades. When negative voltage was applied the strips relaxed and elongated, indicated by a negative slope on the distance graph.

A feature of the data that was not expected was the overall elongation of the strip throughout the actuation. A creep phase was conducted prior to actuation in which the strip was expected to elongate, however it was not expected that the strip would continue to creep once the actuation began. The reason for this is unknown, however some speculations are that the load of the water tank was too large and caused the strip to continue elongating past the creep phase or the creep phase was not long enough and a state of lower static stress was not yet attained prior to beginning the actuation. One strain test was conducted with a creep phase of 45 minutes, but overall elongation during actuation was still observed. In terms of the load applied to the strip, it was slightly larger than 0.2 N for most actuations. As suggested by Nathan Bradshaw, the water tank was filled close to the brim with water for each test, weighing approximately 30 g (greater than 0.2 N). This did not impact the success of the project, however, the cause of the overall elongation should be further investigated with the use of the instrument.

Overall, the data acquired from strain testing showed that the instrument was capable of detecting the minor movements of the strip during actuation, and the movements were consistent with what was expected. These observations help prove that the instrument functions well, and meets the needs of Dr. Murphy and her research team.

Modifications Made to Original Proposed Design:

Some modifications to the project were made during the course of the implementation period. First off, the initial design planned for a wire to suspend the water tank, however this was changed to fishing line due to kinking and bending of the wire that caused it to not hang perfectly vertical. The fishing line was a better fit since it did not kink and hung straight. Figure 10 shows the instrument

assembled with the wire that does not hang straight, and Figure 11 shows the instrument assembled with the fishing line that does hang straight.



Figure 10: *Water tank hanging from wire*



Figure 11: *Water tank hanging from fishing line*

The next modification made was that instead of sealing the electrode leads permanently in the rubber stopper with glue, like initially planned, yellow sealant tape was used. The sealant tape provided an air tight seal while also allowing the electrode leads to be adjusted if needed. This ended up being very useful, making it possible to rotate the leads or adjust their height while the instrument was assembled. This modification also allowed for varied lengths of strips and gold foil to be used, as well as a less precise solution level since the lead heights could be adjusted.

Another modification made to the original design was adding a metal triangular piece to the end of the fishing line that attached to the base of the actuator strip (see Figure 13). The first couple of times the instrument was set up it was difficult to place the fishing line perfectly in the middle of the strip in order to provide even tension (see Figure 12), so a triangular piece of wire was attached to the fishing line in order to make it easier to assemble and to apply a more evenly distributed load.

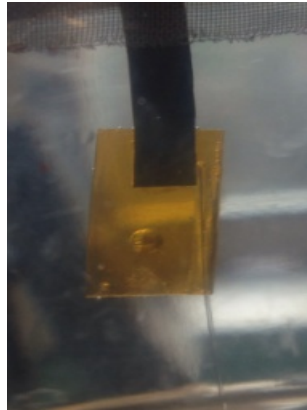


Figure 12: Fishing line w/out wire triangle

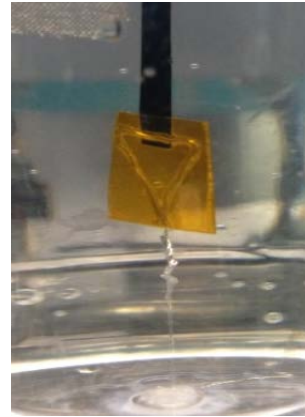


Figure 13: Fishing line w/ wire triangle

Lastly, since a new calibrated laser was purchased, the stability assessment was no longer necessary. The MSA was also eliminated from the project because the instrument is currently only set up by a few trained people, and the instrument’s software program is making the measurements, recording them, and storing them. This means that there is very little human interaction to cause bias in the measurements. The control chart sent by Micro-Epsilon can be seen in Figure 6.

Timeline: Predicted vs. Actual

Table 2: Predicted Completion of Tasks (yellow) vs. Actual Completion of Tasks (blue) for Project Implementation (green indicates overlap of predicted and actual task completion).

Task	12/9-12/13	1/7-1/11	1/12-1/18	1/19-1/25	1/26-2/1	2/2-2/8	2/9-2/15	2/16-2/22	2/23-3/1	3/2-3/8	3/9-3/15	3/16-3/21	4/1-4/5	4/6-4/12	4/13-4/19	4/20-4/26	4/27-5/3	5/4-5/10	5/11-5/17	5/18-5/24	
Assessment of Demo Laser	Green																				
Purchase Equipment/Materials		Green																			
Collect Available Equipment/Materials		Green																			
Modify Submersion Cell			Green																		
Modify Rubber Stopper			Green	Blue																	
Make Hanging Water Tank			Green																		
Set-up/Configure Laser				Yellow									Blue	Blue	Blue						
Stability Assessment of Laser				Yellow	Yellow																
Conduct/Analyze MSA						Blue	Yellow														
Assembly						Blue	Green						Blue								
Determine Quantity of PBS Solution						Blue		Yellow													
Determine Quantity of Load						Blue		Yellow													
Perform Actuations						Blue	Blue	Blue	Yellow	Yellow						Blue		Blue	Blue	Blue	Blue
Write Procedure											Yellow	Yellow									

The project was extended 8 weeks due to the delay in receiving the laser displacement meter. Table 2 shows the predicted timeline (in yellow) overlapped with the actual timeline (in blue). The green squares indicate the overlap of planned and actual completion of tasks. The project got off to a good start in terms of staying on schedule. In the first week of winter quarter, Dr. Murphy informed me that she was applying for a grant to purchase the laser, and that it would not be granted until the end of January, and therefore the laser would likely arrive in mid-February. With this in mind, I altered the timeline and planned to complete the tasks that didn't require the laser first. I stayed on track with this plan, and all tasks that did not require the laser were completed by mid-February. However, by this point, the laser was further delayed due to the Western purchasing department losing the order. At this point in the quarter, an extension request was submitted and approved. In an attempt to keep the project moving without the laser, some actuations were run without the laser once all the components of the instrument were made. We set up a video camera focused on the water tank to see if any movement would be captured on camera, but the movements were too minor to see in the footage. We did this 3 days over the course of 3 weeks, and even though strain measurements weren't able to be collected, this time was helpful in working through the setup and identifying necessary modifications that were mentioned earlier. The laser continued to be delayed as the quarter progressed and did not arrive until the Friday of dead week. No work was done on the project for a few weeks at the end of winter quarter because all tasks left to complete required the laser displacement meter. Once the laser's arrival was confirmed, the project extension was finalized to extend 8 weeks into Spring Quarter. At the start of spring quarter, the setup of the laser was much more complicated than expected since it was not the same as the demo that was sent. Nathan Bradshaw was extremely helpful and took care of the figuring out the electrical wiring and setup of the laser. The laser was finally ready to be implemented into the instrument assembly by the 3rd week of the quarter, and after that point, actuations were run almost weekly from that point on and the procedure was written over the last two weeks. Although the actual timeline deviated largely from the predicted timeline, it was due to unexpected complications such as the delay in the laser's arrival and the complicated laser preparation. All tasks were completed by the end date, and adjustments were made to the timeline order to accommodate for the delay in the laser's arrival.

Budget: Predicted vs. Actual

Table 3: Predicted vs. Actual Budget

Description	Predicted Cost	Actual Cost	Qty.	Predicted Total Cost	Actual Total Cost
Fishing Line		\$2.99	1		\$2.99
Laser Displacement Meter	~\$2600 [12]	~\$2600	1	~\$2600	~\$2600
Epoxy Glue	~\$24 [7]	\$7.50	1	~\$24	\$7.50
Polystyrene Cement	\$3.29 [8]	\$1.99 + \$2.50 in shipping	1	\$3.29	\$4.49
Rubber Stopper	\$3.95 [9]	\$2.25+ \$8.95 in shipping	1	\$3.95	\$11.20
Plastic Container 8.4 oz clear PET (5.021" H x 2.21" Dia)	\$0.33 [10]	\$0.34+ \$8.92 in shipping	1	\$0.33	\$9.29
Polystyrene Sheet (White)	\$6.40/42x72" sheet [11]	\$0	5x5"	~\$0.06	\$0

Alligator Clip	\$0	\$0	2	\$0	\$0
Gold Foil	\$0	\$0	1	\$0	\$0
Polyimide Tape (roll)	\$0	\$0	1	\$0	\$0
Platinum Mesh (25x25mm)	\$0	\$0	1	\$0	\$0
Wire	\$0		±	\$0	
Three Prong Clamps	\$0	\$0	2	\$0	\$0
Stand	\$0	\$0	1	\$0	\$0
Potentiostat	\$0	\$0	1	\$0	\$0
Computer	\$0	\$0	1	\$0	\$0
PBS Solution	\$0	\$0	NA	\$0	\$0
Actuator Films	\$0	\$0	NA	\$0	\$0
Sealant Tape	\$0	\$0	6"	\$0	\$0
Totals				~ \$2632.57	~\$2635.47

Table 3 shows the predicted budget vs. the actual budget. The predicted vs. actual total costs were very similar, proving the project did not largely deviate from the proposed plan and met budget expectations. The grant awarded to Dr. Murphy covered the cost of the laser displacement meter, and all other items were either available for use at Western or were purchased and very low in cost. This instrument is economical and all components, aside from the laser displacement meter, can be cheaply and easily replaced if needed.

Ethical Issues

There are very few ethical issues related to this project. The main ethical consideration of this project regarded operator safety. All safety requirements were followed while working in the Chemistry and PET labs, resulting in no hazardous situations. Safe handling of the laser was also practiced. Care was always taken when the laser was on to ensure that the beam was never pointed at a person, and laser set up and wiring was always checked and confirmed by Nathan Bradshaw prior to being turned on. Instrument safety requirements are also included in the operating procedure. The potential ethical issue of purchasing a used laser displacement meter was avoided since a new laser was purchased from a credible company and came calibrated with 12 month warranty.

RECOMMENDATIONS FOR FUTURE WORK

Recommendations for future work include a continuation of strain testing, an exploration of creep phase time and overall elongation during actuation, and an exploration of hanging load quantity. Continuation of strain testing is important for acquiring more strain data for analysis. It will also help in optimizing the operating procedure and identifying any further modifications that may need to be made to improve the instrument. An exploration of creep phase time would be beneficial in identifying whether the strip ever hits a maximum point of elongation. It could also help identify the cause of the overall elongation of the strip during actuation. As mentioned previously, a load greater than 0.2 N was applied to the strip in the strain testing conducted during the implementation of the project. Therefore, an assessment of how different loads impact the strain results would be beneficial in gaining a better understanding of the strips' characteristics, and could also help identify the cause of the overall elongation of the strip during actuation. To further assess the quality of the instrument, I recommend that the hanging load be weighed before and after the actuation to identify if any solution leaks out of the submersion container during testing. This was not done during the tests conducted, but should be in the future.

CONCLUSION

In conclusion, this project was successful. All objectives, functions, and constraints were met, and all deliverables were completed. The instrument provides a way to collect strain measurements that will help Dr. Murphy and her research team gain more information about the properties and potential of the artificial muscles being developed at WWU. An operating procedure was developed and written that will help new and existing users of the instrument properly set up and run the instrument and laser. Through the strain testing conducted so far, the movements of the strips have correlated with what was expected, and interesting features to be further investigated were identified. The project went over the initial budget, however this was not a problem thanks to grant money obtained by Dr. Murphy to purchase the laser. The project also went past the initial deadline, however this was due to a delay in the arrival of the laser displacement meter. For this reason the project was extended, and all tasks were completed within the approved extension period.

ACKNOWLEDGEMENTS

Personnel

Sponsor: Dr. Amanda Murphy

Adviser: Nicole Larson

Murphy Group Members: Nathan Bradshaw, Jesse Larson, Carly Klemke, Sean Severt

Facilities

Chemistry Research Lab

PET Soft Tooling Lab

Physics Research Lab

Equipment

Drill Press (PET Soft Tooling Lab)

Band Saw (PET Processing Lab)

Keithley Potentiostat/Computer (Chemistry Research Lab)

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 [12] Email conversations with Jerry Carayanis, Microepsilon Regional Sales Manager Nov. 14-Nov. 22, 2013.

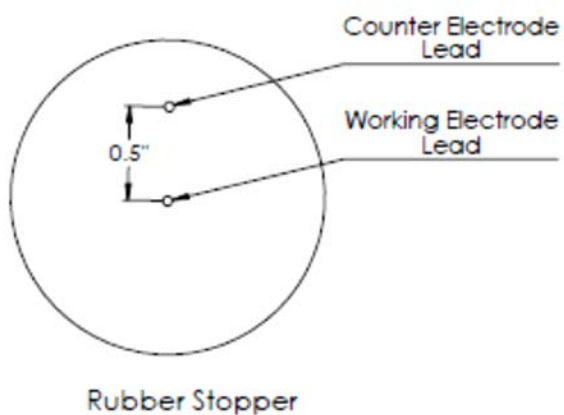
APPENDICES

Appendix A

Conversion of 0.2 N to cubic inches of water:

$$(0.2 \text{ N}) * \left(\frac{\sim 101.9716 \text{ g}}{1 \text{ N}} \right) * \left(\frac{1 \text{ cm}^3 \text{ H}_2\text{O}}{1 \text{ g H}_2\text{O}} \right) \approx 20.4 \text{ cm}^3 (\text{mL}) * \left(\frac{1 \text{ in}^3}{\sim 16.387 \text{ cm}^3} \right) \approx 1.2445 \text{ in}^3$$

Appendix B



Appendix C

