

## xDI - Cartilage Bioreactor

Client: Prof. Corinne Henak

Faculty Consultant: Prof. Corinne Henak (ME); Prof. Paul Campagnola (BME)

Team: Jeffery Guo (ME Admin & Accountant)

Emilio Lim (BME BWIG & BSAC)

Griffin Radtke (ME Operational Leader & Communicator)

Sydney Therien (BME Operational Leader & Communicator)

### Status

Report Date: 03/08/24

Next Milestone: Working Prototype

Deadline: 3/18/24

Status: on schedule

### Technical Summary

This week the team focuses on finalizing plans to start fabricating the housing of the bioreactor. Sydney and Griffin will be looking into using a combination of machining to put the housing of the bioreactor together. While Sydney and Griffin focus on getting a physical prototype of the bioreactor up, Emilio and Jeffery continue to experiment on modulating and controlling the VCA. Emilio and Jeffery made some progress by using an Arduino and a power supply to drive the VCA at 1Hz. More progress still needs to be made to ensure they meet the client's requirements.

### New Tasks

Task Name	Description and Concrete Outcome	Owner	Est. Time [hrs]
Estimate friction and impact of wear for Drylin Q Flange bearing	Pulled numbers from Drylin website and made plots to get a sense of how long the bearing could be in operation and how much of an issue friction would be.	ST	2.5
Continue testing H-bridge	Continue testing H-bridge to get a triangle output	JG/EL	3
Revamp CAD for Machining	Make modifications to existing CAD for machining-purposes	GR	6

## Technical Section

Author: Sydney Therien

Editor: N/A

Estimate friction and impact of wear for Drylin Q Flange bearing	Pulled numbers from Drylin website and made plots to get a sense of how long the bearing could be in operation and how much of an issue friction would be.	ST	2
--	--	----	---

After the TeamLab consultation steered the team in the direction of using the Drylin Q flange bearing (essentially for cost/lower complexity reasons), I wanted to see whether or not use of this bearing would fulfill the design specifications. This involved assessing the friction force that would be produced between the walls and the shaft, and the lifetime of the product using wear resistance.

To assess friction, I first called igus to see if the CoFs on the website were static or dynamic (it did not say). They said that the values would be comparable between the two, so for estimation purposes, I used the provided values for low and high loads (I'm fairly certain this is a low-load application, but I wanted to visualize both). Using  $F_f = \mu \cdot N$  and a range of normal forces from 0-3N (hopefully much more than we would hope to experience) and multiplying by four for the number of walls that experience the friction, I produced this plot.

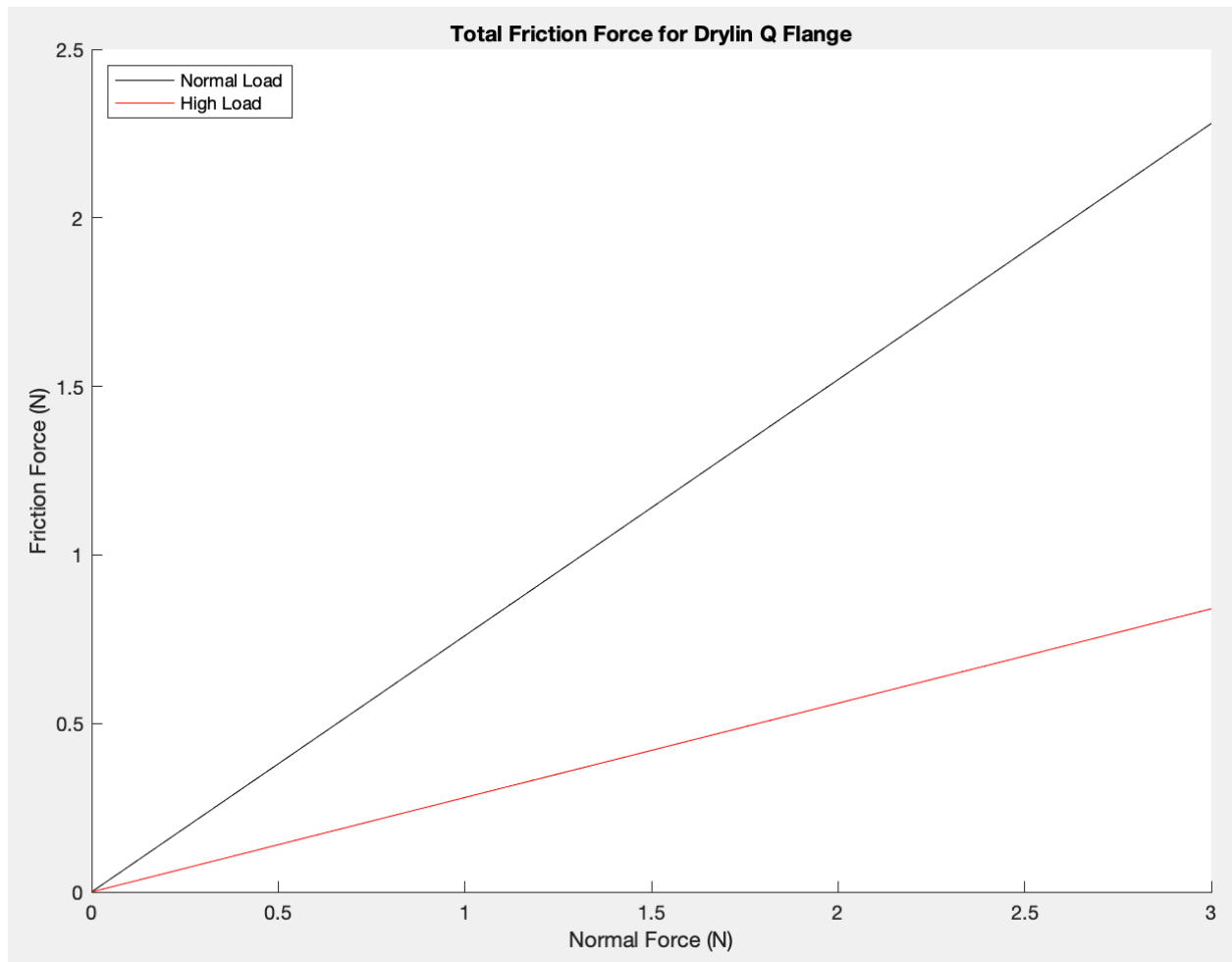


Figure 1: Plot describing the total friction force opposing actuator output force for the Drylin Q flange bearing over a range of normal forces.

Since the force output range for the VCA goes up to ~12N, this friction force is easily compensated for if the device is calibrated properly. However, the normal force fluctuates depending on the amount that the walls with low-friction gliding material are worn down. I wanted to assess how fast this process happened to both see how often the device would need to be recalibrated and how long the bearings would last before the low-friction gliding material

wore down enough to necessitate replacement.

I pulled wear coefficients from the Drylin website. These were given in  $\mu\text{m}/\text{km}$ , which I interpreted as “the gliding material will wear down this many microns if 1 km of shaft slides across it.” These wear coefficients were given for many shafts, the lowest two of which for our gliding material (iglide J) were hard-anodized aluminum and hard-chromed. Drylin sells a [hard-anodized aluminum shaft](#) compatible with this bearing for \$101.19/m. I assumed that with each actuation, the shaft travels along the entire length of gliding material (which is a significant overestimate but provides us with a solid factor of safety). Using the wear coefficients, the distance of gliding material covered in one second (twice the length of how much is inside the bearing), and some basic math, I calculated how long the bioreactor could be in operation. This is shown below.

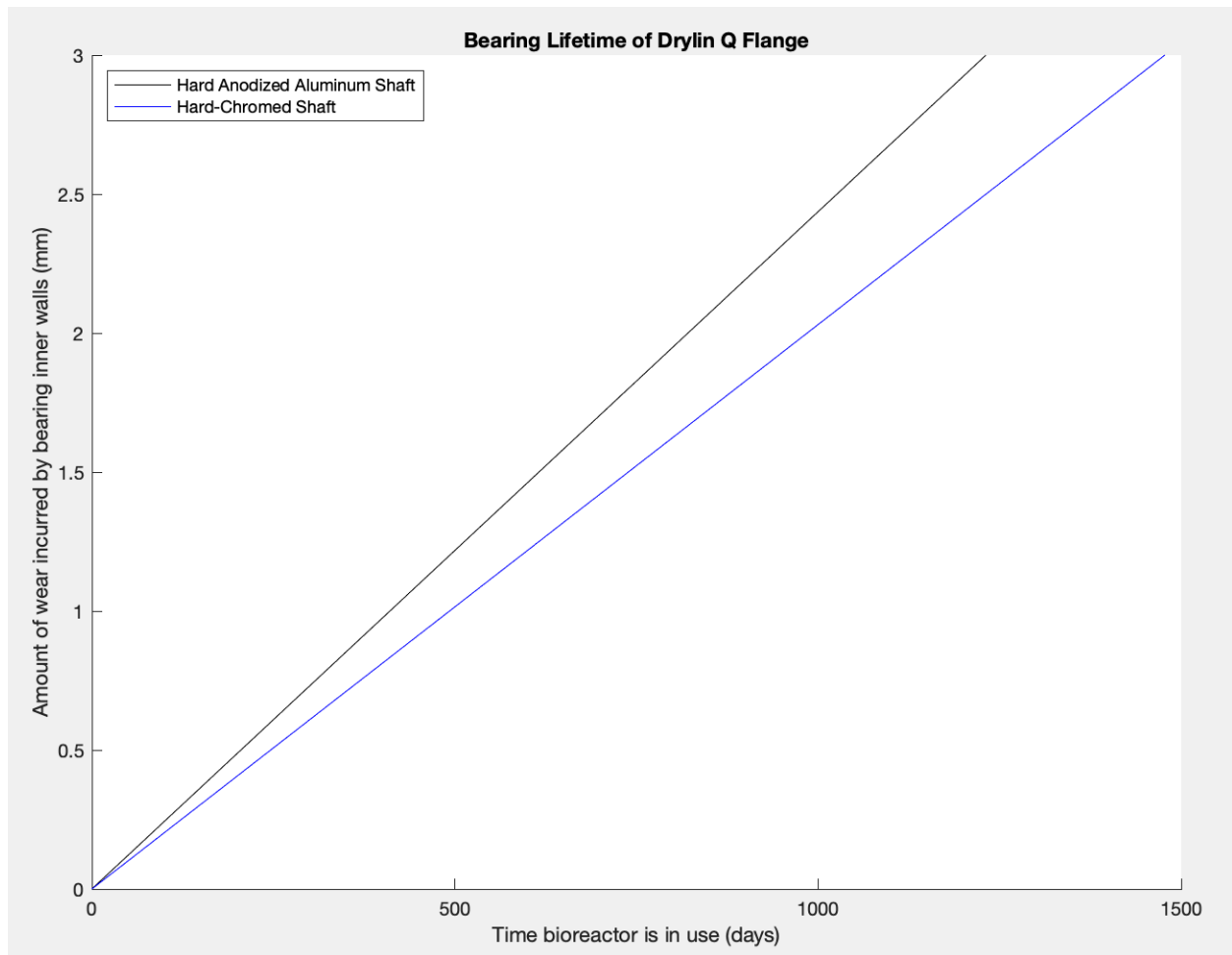


Figure 2: Plot describing how long the bioreactor is in continuous operation versus how much that operation wears down the walls made of gliding material.

What Figures 1 and 2 show is that the Drylin bearings have a much longer life than previously thought and seem to be a fitting bearing for the bioreactor. With this information, I hope that the team can be more confident moving forward with incorporating them into the design. I also sent igus an email summarizing what I did in these calculations with these plots and asked for anything they had on how long the bearings would last under our conditions, so

I'm watching my inbox for their reply and hopefully they have some information or maybe even some feedback on these plots for me.

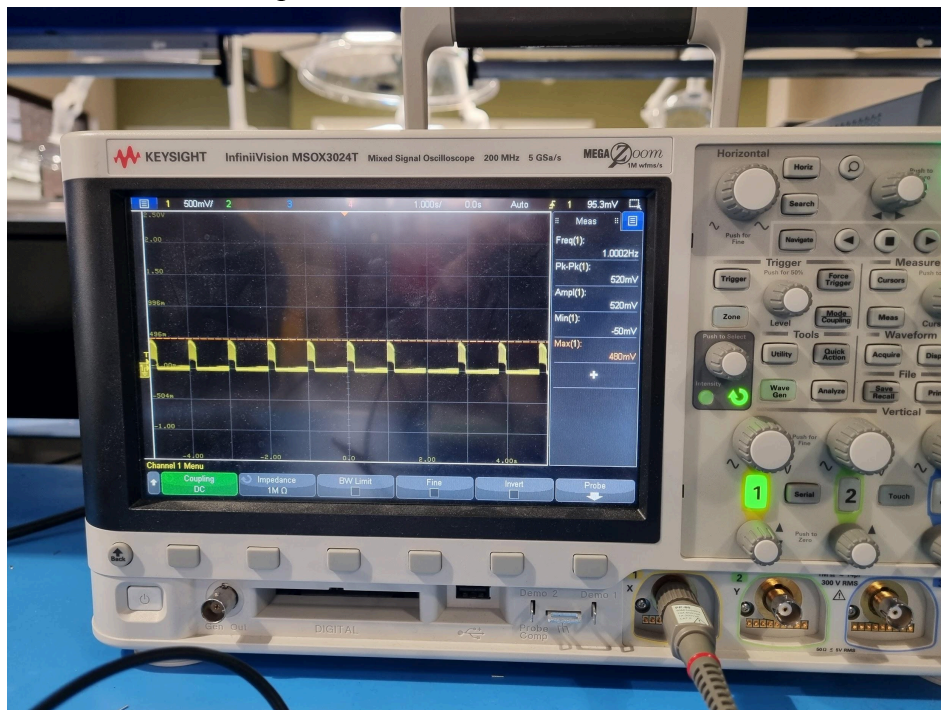
Author: Emilio Lim

Editor: Jeffery Guo

Continue H-bridge testing	Continue testing H-bridge to get a triangle output	JG/EL	3
---------------------------	--	-------	---

This week Emilio and Jeffery continued to test the VCA using the H-bridge from the L298N motor controller. We were successful in getting an output with sufficient current to allow the VCA to oscillate at 1Hz, following a square wave output. When we were trying to change the voltage output from the H-bridge by changing the value of the enable pins, we found that the VCA makes a high pitched siren-like noise. This noise could not be heard when the enable pin is set to the max value. A clearly defined square wave output can also be seen when the enable is set to max value from the oscilloscope. Any value lesser than 255, which is the max value, would produce the siren-like sound and a square wave with some noise as seen in the picture below. A short video of the experiment is uploaded onto the drive under media > testing 3/6.

To continue moving forward, we will need to be able to change the voltage output, ensure the output signal generated is a triangle-like wave, and make sure there is no additional sound. Patrick suggested we look into finding a setting that would allow a triangle wave output by changing the value of the enable pin.



Author: Griffin Radtke

Editor: N/A

Revamp Machining	CAD for	Make modifications to existing CAD for machining-purposes	GR	6
---------------------	------------	--	----	---

After further discussion regarding the plan(s) for fabrication going forward, we've decided to proceed in two separate directions: Sydney will work on an acrylic model, while I'll make slight modifications to the existing design to repurpose it for machining (i.e., the previous model was designed w/ 3D-printing intent, hence the non-machinable architecture at certain points). Along with slight revisions in design intent, several elements within the model are removed, as the improvements in tolerancing offered by machining make several features in the prior design redundant. Overall, timeliness of machining/fabrication is now the main concern, which is reflected in several of the design modifications.

Looking forward, after discussion with the team, analysis of the CAD will be prioritized during the faculty & TA meetings, with – assuming approval/consensus in both – an order for fabrication to be placed by the end of the week (3/15).

# Gantt Chart

Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Jan		Feb				Mar				Apr				
Task	24	31	7	14	21	28	6	13	20	27	3	10	17	24	1
<b>Individual Presentations</b>					X										
Bioreactor Housing and Bearings															
Control with One VCA															
<b>Working Prototype</b>										O					O
Full Bioreactor CAD Model				X											
Fabricated Bioreactor															
Circuitry with All Six VCAs															
<b>Final Review</b>										O					O
Design Specification Validation															
Bioreactor Assembly with Circuitry															

**X = Completed Tasks, O = Milestone Deadlines**

## Old Tasks

Task Name	Description and Concrete Outcome	Owner	Est. Time
Integrate MyDAQ with motor controller or other circuitry to get desired output	Experiment with different circuit components (e.g., MOSFET, power op amp, H-bridge, etc.) to obtain a force of 6N at 1Hz using the myDAQ and/or Maxon motor controller	EL/JG	3
Finalize bearing options	Flesh out bearing design matrix with all final options and quantitative specs.	ST	3
CAD Refinement & Analysis	Run SolidWorks FE static simulation to verify feasibility of compressive interface, refine model graphics	GR	3
Troubleshoot myDAQ	Troubleshoot potential errors in the myDAQ	JG	2
Work with Arduino and current regulator	See if some codes of the arduino can be used to generate a sine wave in lieu of the current regulator from the ME library	EL	2
Design consultation with TeamLab regarding fabrication and bearings	Met with TeamLab personnel to ask about the cost/feasibility of fabricating the device and solicited their opinion on what bearings to use.	ST	1
New CAD with fabrication feedback from TeamLab	Turned the TeamLab's recommendations for the bioreactor into a full SolidWorks file which will be possible to machine.	ST	7.5
Estimate 3D-Print Costs	Calculate exact costs of 3D-printing previous model, itemize budget	GR	1
Test and develop working system of circuitry/electronics to operate VCA	Continue experimenting with electronics/other components (e.g., motor controller, H-bridge, power supply, myDAQ, Arduino) to develop functioning system that can operate the VCA	JG/EL	3
Develop rough calibration curve for voltage input and force applied	Create a rough calibration curve for voltage input for the VCA vs. force outputted by the VCA using the triangle PCB	JG/EL	1



## Previous Work

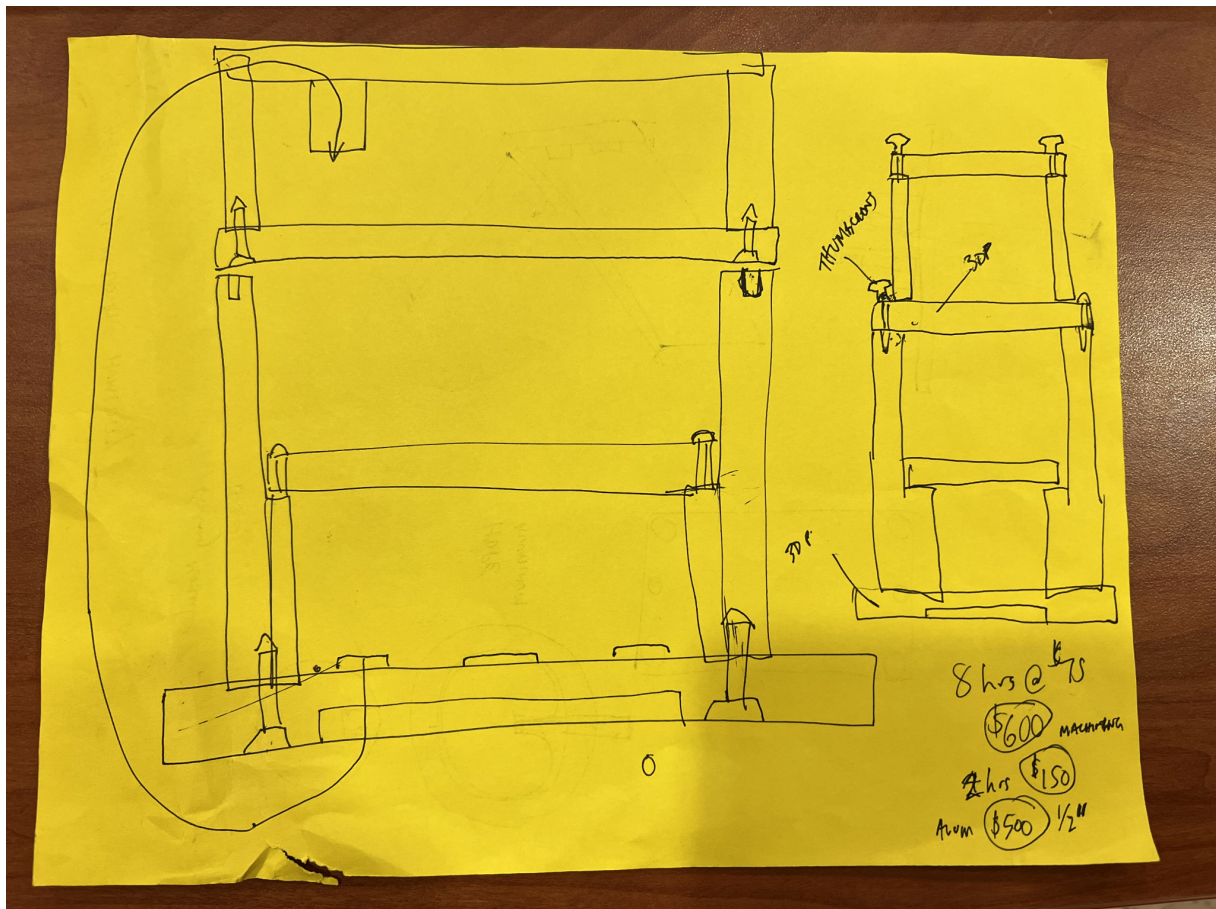
Author: Sydney Therien

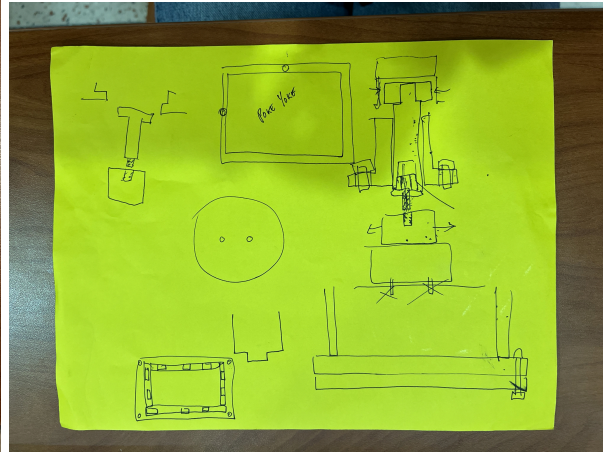
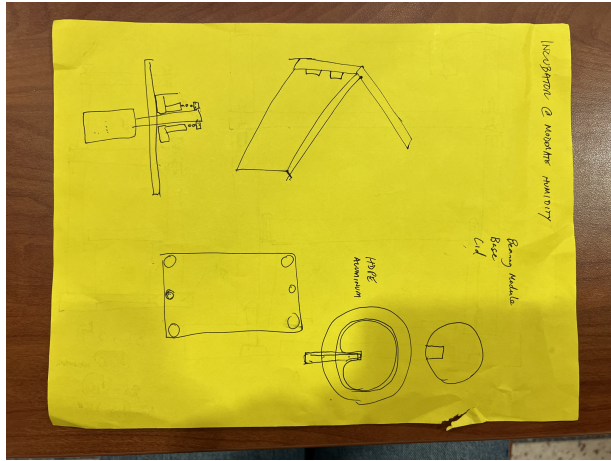
Editor: N/A

Design consultation with TeamLab regarding fabrication and bearings	Met with TeamLab personnel to ask about the cost/feasibility of fabricating the device and solicited their opinion on what bearings to use.	ST	1
---	---	----	---

In order to start the process of turning the housing CAD into a physical device, I met with TeamLab personnel on Tuesday of this week (2/27). The goals were to get a price estimate on contracting them to do the fabrication and to solicit their opinion on how we should proceed with bearings.

We started by discussing changes that should be made to the CAD so that it can be machined. This involved creating some panel pieces out of what previously were boxes and making flatter, smaller layers that could either be 3D printed or laser-cut. Below are photos of the rough sketches they produced in order to illustrate their desired changes.





In the lower-right corner of the first image was the tallying of the price for their work. It comes down to between \$1200-1300, which includes materials (using aluminum) and labor. This is a significant portion of the remaining ~\$2000 budget. Should we fabricate with the TeamLab, the expensive but ideal linear ball splines from Misumi could not be purchased.

Regarding the discussion about bearings, I was strongly cautioned against fabricating a shaft for the ball bearing flanges in-house or even contracting the TeamLab to. Apparently they require an extreme level of precision in the manufacturing process that would make successful fabrication unlikely. They also said that the Misumi ball splines might be overkill, and that the Drylin square flanges would likely be effective enough in this context.

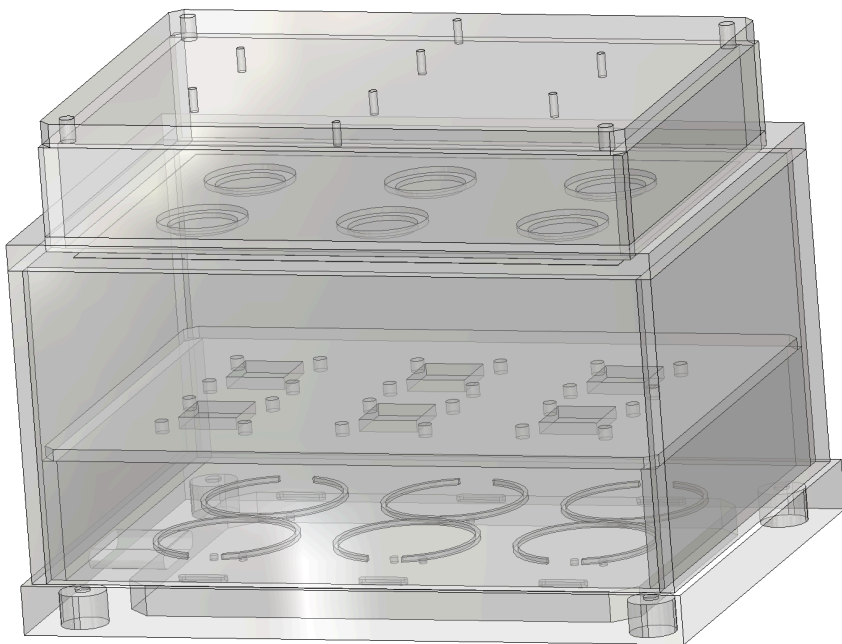
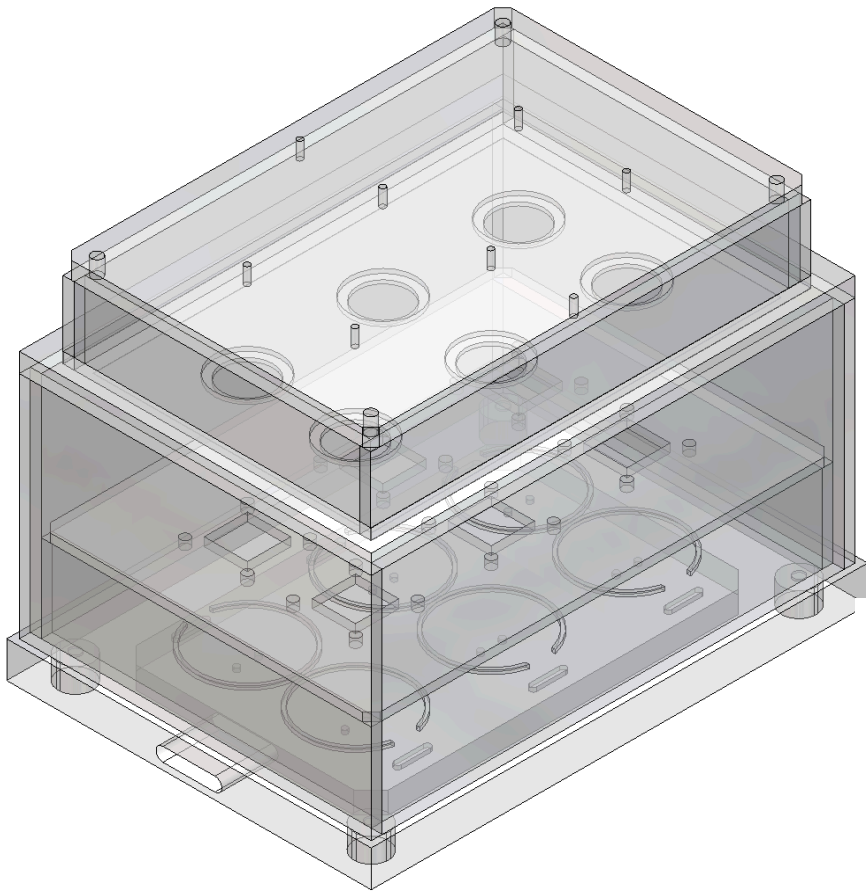
We also discussed the value of creating a prototype of entirely laser-cut acrylic and 3D printed sample tray and base. They said that prototyping is invaluable when taking something out of CAD because it allows you to see things in a physical 3D space that you might have missed in SolidWorks. I would agree that it would be valuable to build a prototype, but only if it can be done very cheaply (\$50-100). I'll be stopping into the MakerSpace soon to get a price estimate on fabricating my new CAD. The team will discuss fabrication budgeting early next week and hopefully start to make some decisions (as there is a finite amount of time left in the semester).

Author: Sydney Therien

Editor: N/A

New CAD with fabrication feedback from TeamLab	Turned the TeamLab's recommendations for the bioreactor into a full SolidWorks file which will be possible to machine.	ST	7.5
--	--	----	-----

After the meeting with TeamLab, I was able to modify the CAD such that it could be fabricated in the way they recommended. Below are some photos:



Major changes include implementing panels to make the boxes and flattening the trays. The bearing module's panel rests on a shelf in the wall. The new "lid" includes a base that is a bit wider than the sample chamber. This was added so that thumbscrews could be added to each of the corners to facilitate easy removal and setup of samples. Fasteners would still need to be added to this CAD, though TeamLab did say that if we were going to build a prototype, the CAD doesn't need to be perfect and more needs to facilitate building a real object. The team will discuss this new CAD and how we will proceed early next week.

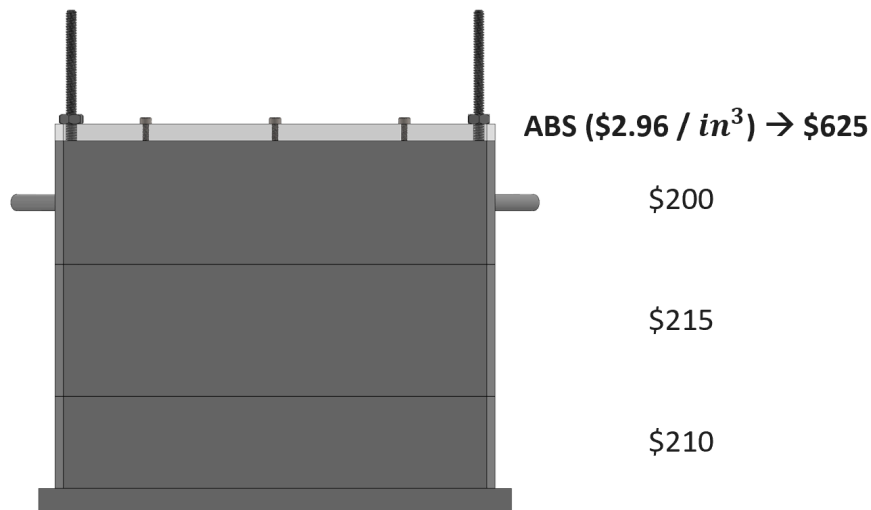
Author: Griffin Radtke

Editor: N/A

Estimate 3D-Print Costs	Calculate exact costs of 3D-printing previous model	GR	1
-------------------------	---	----	---

To have a fully informed discussion regarding the two fabrication types, I formally computed the exact (rounded, to avoid ¢) price of 3D-printing the first three modules, using [ABS](#) as it most closely matches our demands (the latter, being acrylic for both, was not included in the graphic below; however, this would be ~\$50 for a 10 mm thick piece matching our lid dimensions).

Additionally, just as a further note, I've roughly itemized the budget for context. Overall, the team has a \$5,000 budget: of that, 6x Thorlabs VC125C/M will cost ~\$3,170 at current pricing (i.e., Thorlabs' prices have risen slightly since purchasing the first VCA); further, purchasing the square bearings (i.e., @ \$63/bearing) will cost a further \$380 – unrelated, but consideration of guide rails might be more cost effective on this front and merits attention over the next week. Broadly, then, presuming the shafts cost only an additional one to two hundred dollars, we're left with \$1,200 for our electronics and housing, as well as any potential prototyping.

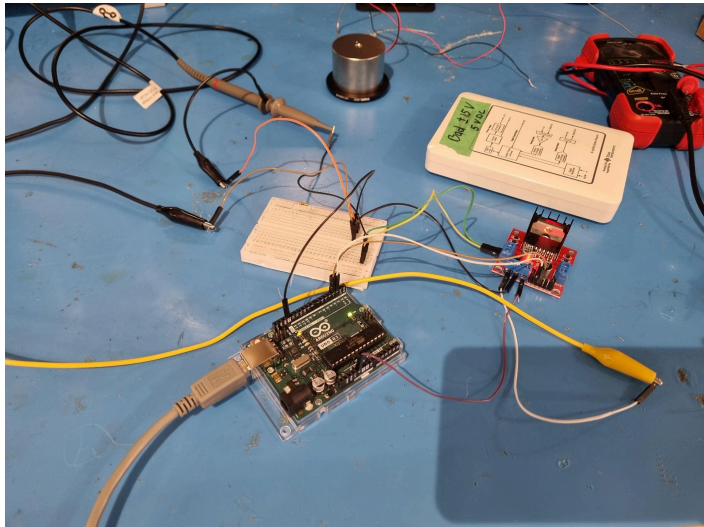


Author: Jeffery Guo

Editor: Emilio Lim

Test and develop working system of circuitry/electronics to operate VCA	Continue experimenting with electronics/other components (e.g., motor controller, H-bridge, power supply, myDAQ, Arduino) to develop functioning system that can operate the VCA	JG/EL	3
---	--	-------	---

Jeffery and Emilio continued testing various circuitry and electronics components to develop a functioning system which can operate the VCA as desired. They purchased an L298N motor driver (i.e., H-bridge) from the Makerspace shop. With the H-bridge receiving a square wave voltage input from the myDAQ, the VCA or oscilloscope connected to the motor output, and power supply connected to the power input, we expected the VCA to actuate, but nothing interesting happened. The oscilloscope measurements showed a small square wave output, insufficiently large to power a VCA. Emilio also tested the Arduino in place of the myDAQ, but the output was even smaller. Moving forward, Jeffery and Emilio plan to continue testing and troubleshooting as well as consult Patrick to determine why the H-bridge may not be working as expected with the VCA.

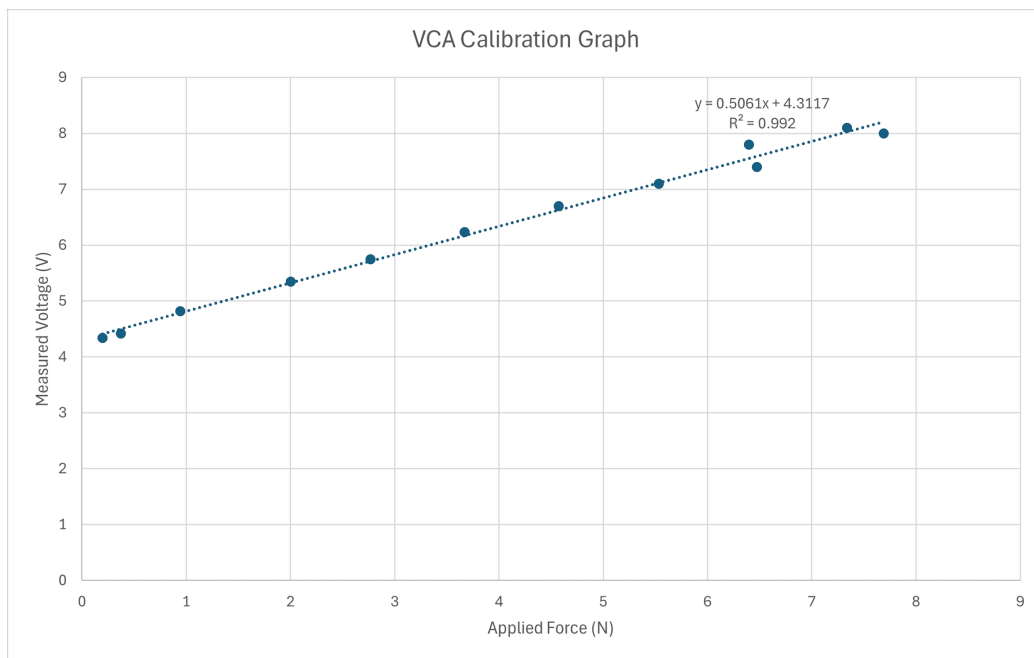


Author: Jeffery Guo

Editor: Emilio Lim

Develop rough calibration curve for voltage input and force applied	Create a rough calibration curve for voltage input for the VCA vs. force outputted by the VCA using the triangle PCB	JG/EL	1
---	--	-------	---

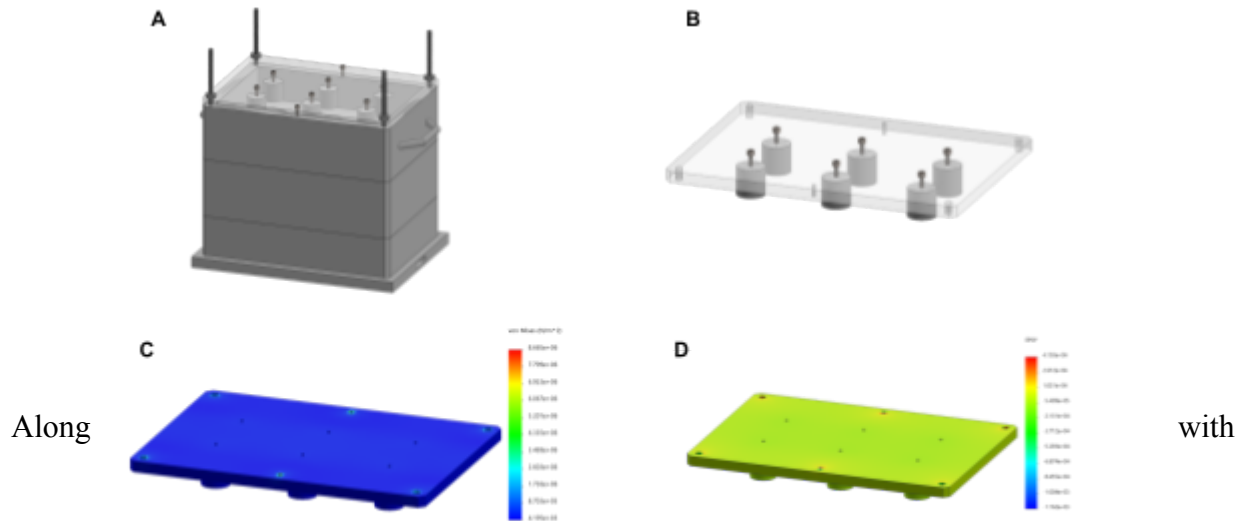
Jeffery and Emilio used the triangle wave generator PCB to create an approximate calibration curve of voltage input vs. force applied for the VCA. The results show a roughly linear relationship between voltage and force, as expected. Washers were used as weights to simulate force application, with each weighing roughly 20 g, or 0.2 N. The VCA is able to apply over 6 N of force, and it has a maximum voltage output of nearly 8-9 V.



Author: Griffin Radtke

Editor: N/A

CAD Refinement & Analysis	Run SolidWorks FE static simulation to verify feasibility of compressive interface, refine model graphics	GR	3
---------------------------	---	----	---



**Figure (Summary).** Overview of completed model, compressive interface (for reference), and SolidWorks FE static simulation of acrylic compressive interface under 10 N loading (10 N / PTFE cylinder → 60 N total). A) Dimetric view of completed, fully developed SolidWorks model. B) Dimetric view of acrylic & PTFE compressive interface (acrylic: 10 mm thickness). C) von Mises stress, computed primarily as a sanity check to ensure stress concentrations were present where expected. D) Engineering strain (along y axis) to verify negligible deflection is present in the acrylic surface.

finalization of the CAD file (A), a FE study within SolidWorks was ran to ensure the acrylic compressive lid (B) could withstand the load profile of the bioreactor (i.e., ~10 N maximum). Von Mises (C) stress - to ensure stress concentrations existed about the bolt locations - and strain in the vertical axis (D) - to verify minimal deflection - results were generated. Further, a max normal stress failure criterion was applied (i.e., to best estimate brittle failure), with a minimum factor of safety of 3.3 computed from the maximum loading condition. With these results validating the material's application, the team will proceed with laser-cutting acrylic for the compressive interface lid following selection of a bearing and agreement on fabrication of the remaining bioreactor modules.

Author: Sydney Therien

Editor: N/A

Finalize bearing options	Flesh out bearing design matrix with all final options and quantitative specs.	ST	3
--------------------------	--	----	---

In preparation for the individual presentations, I wanted to make sure that I had

consolidated all of my research on bearings. I updated the design matrix from last week so that it reflected all of the bearings we are seriously considering. Those are the [Drylin O Flange Bearing](#), the [Misumi Round Flange Linear Ball Bearing](#), and the [Misumi Standard Ball Spline](#) (products are hyperlinked). The Misumi ball glide is no longer being considered due to the fact that it doesn't inhibit rotation. After learning that the coefficient of friction of the Drylin bearing is several orders of magnitude larger than that of the Misumi bearings, the team is leaning more towards one of the Misumi ball bearing options. The main difference between the two is one comes with a compatible shaft, and the other requires that the shaft be purchased or machined separately. I have a consultation scheduled with TeamLab for next Tuesday morning where we will discuss the fabrication of the housing and get a price estimate on this (whether we 3D print or contract someone to machine it for us). I will also ask about the feasibility of fabricating the shaft for the Misumi Flanged Ball Bearing. Knowing how much the housing (and potentially the shaft) will cost will inform how much we have to spend on the bearing. From there, we can make crucial decisions about the components we order and our fabrication methods.

	Friction (40)	Shafts (15)	Re-orderability (10)	Cost for all six (35)	Totals
Drylin Square Flange	(%) <a href="#">mu=0.19</a> with stainless steel and ideal smooth finish	(%) Square and almost 1in <sup>2</sup> , very big	(%) Depends on where shaft comes from but bearing is a reorderable product	(%) \$382.92 (+ shafts)	48
Misumi Flanged Ball Bearing	(5/5) <a href="#">mu=0.003-0.006</a> but for the square ones, same design ish so should be similar	(%) Cylinder with race, would need to machine or call to find part	(%) Depends on where shaft comes from but bearing is a reorderable product	(5/5) \$100.20 (+ shafts)	90
Misumi Complete Ball Spline	(5/5) <a href="#">mu=0.003-0.006</a> but for the square ones, same design ish so should be similar	(%) Would need to be tapped or threaded, or could order it this way for more \$\$\$	(5/5) Can order again from a Misumi no issue	(%) \$1170.18	76



Author: Emilio Lim

Editor N/A

Work with Arduino and current regulator	See if some codes of the arduino can be used to generate a sine wave in lieu of the current regulator from the ME library	EL	2
---	---	----	---

The arduino does not necessarily have built in sine wave functions that can be easily used on the AnalogOut pin. I will need to write a separate code to ensure the output is oscillating at 1Hz. Furthermore, through previous experiments, it was noted that there needs to be sufficient current to drive the voice coil. Since the Arduino is not able to output a high enough current, we will need to connect another circuit component such as a power supply and power op-amp to be able to output a higher current.

Another option was using a MOSFET, however, the MOSFET does not handle sine wave signals well and might not be able to generate the signal output we want. This circuit however, still requires an external power supply and an Arduino or microcontroller to generate the signal.

Author: Emilio Lim

Editor: Jeffery Guo

Troubleshoot myDAQ	Troubleshoot potential errors in the myDAQ	JG	2
--------------------	--	----	---

Jeffery and Emilio went to the MakerSpace to test the myDAQ with the VCA. Jeffery previously wrote a LabVIEW block code diagram to enable the MyDAQ to output a sine wave at 1Hz and 3V. Testing the myDAQ with the oscilloscope, it was successfully verified that the desired analog outputs are functional and they can output sine waves with the desired amplitudes and frequencies. We proceeded to connect the corresponding output channel on the myDAQ to the voice coil, but there was no change in movement from the voice coil. This is very likely due to the lack of sufficient current from the myDAQ, as the myDAQ is USB-powered. The maximum output current is roughly 5 mA which is too small. We then tried to integrate the previously obtained Maxon 4Q-DC motor controller with the myDAQ and VCA. Jeffery and Emilio were able to successfully obtain a voltage signal from the motor controller's motor terminal outputs using a power supply and the myDAQ, but not the desired output required to operate the VCA. More work will need to be put in to fully understand the output channels of the Maxon motor or determine if circuitry or components are better suited to achieve the desired output.

Author: Griffin Radtke

Editor: N/A

Housing Development	Aim to finalize all remaining aspects of housing; further, weigh potential fabrication methods.	GR	3-4
---------------------	---	----	-----

Subsequent modules of the bioreactor housing have been completed, with just a sample tray and compressive interface left to design within SolidWorks. Griffin and Sydney will discuss potential

fabrication options for the various modules: for the lower/base modules, 3D-printing is preferred, given the likely time investment required for other fabrication methods; for the sample tray, either milling or 3D-printing are under consideration; and, lastly, laser cutting has been agreed upon for the compressive interface. Overall, conclusion of the design will immediately lead into fabrication, with manufacture and assembly of the box ideally not taking more than a week.

Author: Sydney Therien

Editor: N/A

Bearing design matrix	Weigh the Drylin square flange bearing against a Misumi ball guide to analyze what would be the best fit for the design.	ST	2
-----------------------	--	----	---

In order to create effective force control, the team needs to ensure that the actuator moves as uniaxially as possible. This requires a bearing, which the team is on the lookout for. The two general mechanisms the team is considering are a ball glide/spline and a flange bearing in the shape of a square. Two example products were evaluated in the design matrix below:

	Horizontal Restriction	Rotation Restriction	Shafts	Re-orderability	Cost x6
Square Flange	yes	yes	Need to make shaft start to finish	New shaft from makerspace OR wherever it's purchased (this will depend)	\$382.92 (+ shafts)
Round Ball Guide	yes	no	Need to thread end and would integrate bearing into lid	Can order again from a Misumi no issue	\$153.60

Table 1: Simplified design matrix comparing important parameters from the square flange and round ball glide options.

The results of this matrix are inconclusive. After the team meeting, it was decided that more research should be done into bearings. Adding a flexure to the lid will also be considered. Next week, the team hopes to have a better idea of what kind of bearing (and what specific product) would be the best fit for the bioreactor.

Author: Sydney Therien

Editor: N/A

Order PTFE	Consult with Chanul about the final PTFE product and place the order.	ST	0.5
------------	---	----	-----

With the majority of the device designed, it is time to move forward on the fabrication of some elements. An easy one to start with is the compressive interface, which is the part pictured below:

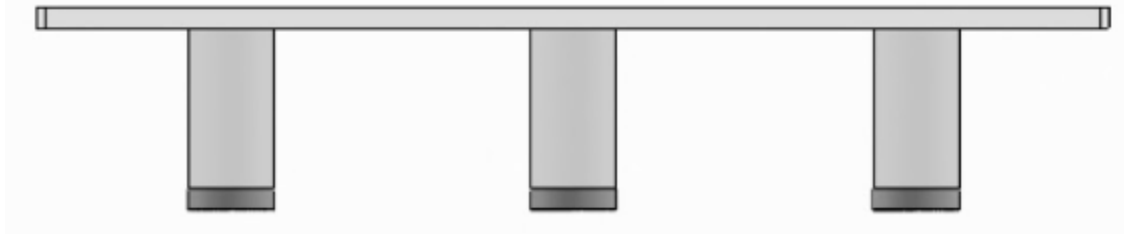


Figure 1: The compressive interface.

The design has been simplified such that the entire pillar will be made out of PTFE. It was initially thought that the PTFE interface would be expensive, but the entire foot-long stock is approximately \$20. Making the entire pillar PTFE will simplify the fabrication process immensely. The PTFE pillars will be tapped and screwed into a lid that fits the dimensions of the bioreactor (with no 3D printing involved). During a team meeting this week, it was decided that Griffin would take point on fabrication of the “base” and “lid” components (pictured in Figure 2) and Sydney would take point on fabrication of the plungers, tray, and compressive interface (pictured in Figure 3). Each person will decide how their components will be fabricated.

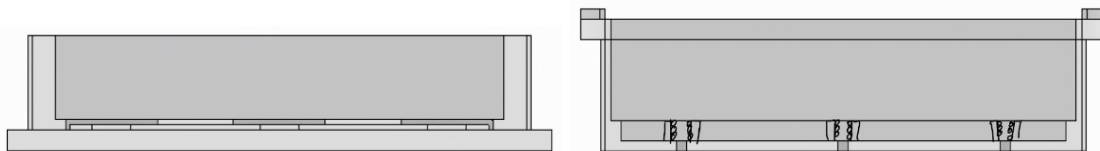


Figure 2: The components that Griffin will fabricate.

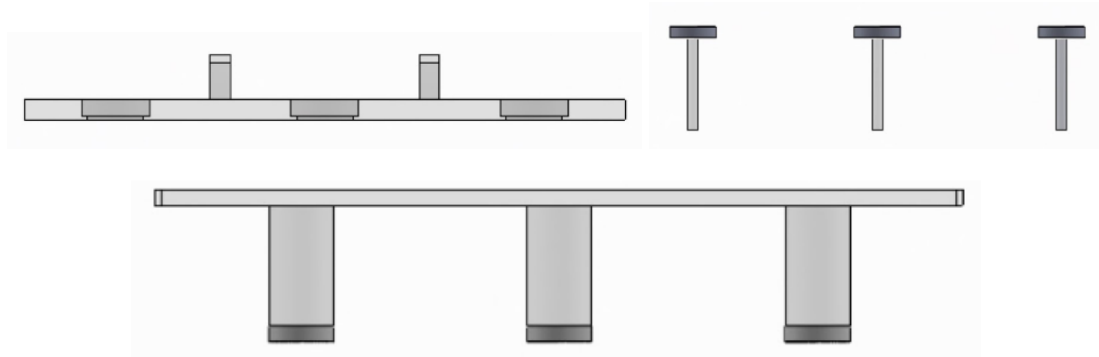


Figure 3: The components that Sydney will fabricate.

Author: Jeffery Guo

Editor: Emilio Lim

Test myDAQ with VCA	Write a LabVIEW VI which outputs the correct, desired voltages from the myDAQ to the VCA. Study how the VCA responds and compare its response to that from the PCB. Determine what else is needed in terms of circuitry (e.g., current regulator, H-bridge).	JG/EL	3
---------------------	--	-------	---

Jeffery created a LabVIEW VI which was written to output a sinusoidal voltage similar in magnitude to what was used to power the VCA using the triangle generator PCB. However, when testing, after connecting the VCA to the myDAQ analog output port and ground and running the VI, the VCA remained stationary. Jeffery and Emilio attempted to measure the output voltage of the analog out using both a myDAQ analog input and a DMM, but did not receive any reliably correct readings. Jeffery and Emilio then tested a basic DC voltage output, which the myDAQ analog input correctly measured, albeit with some noise and error. The signal however was not zeroed out at the when the input was taken off. Thus, the output voltage was not very reliable.

The Makerspace was closed all day on the scheduled day Jeffery and Emilio planned to test, so tests were performed without helpful equipment such as a screwdriver for the myDAQ screw terminals and an oscilloscope for measuring the voltage output from the myDAQ. There is a possibility that the problem is the specific myDAQ being used. The ME 368 lab only lends out faulty myDAQs, and in our case, certain terminals were confirmed to be faulty, but it is still possible that both AO ports are also faulty when attempting to output a non-DC voltage. We will also need to ask Patrick if this is the reason he believes we need a current amplifier/regulator.