xDI - Cartilage Bioreactor

Client: Prof. Corinne Henak
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Status

Report Date: 03/22/24
Next Milestone: Final Report
Deadline: 04/29/24
Status: on schedule

Technical Summary

This week, the team presented the previously (Wk 8) discussed working prototype and received useful commentary, particularly on the circuitry side of things. Going into spring break, the team largely spent the time preparing for the final stretch of the semester. On the housing end, we requested sample parts for the actuation plunger/shaft (i.e., the shaft and the discussed square bearing) from Igus – allowing for work on a 1D bioreactor to begin. Further, we came to a final decision on the myDAQ against Arduino comparison and additionally ran a finite element simulation of the bioreactor's force output on an ideal cartilage sample to provide a 'sanity check' on our forces as well as to provide a preliminary finite element comparison to potential experimental testing in coming weeks. In the coming weeks, we look to quickly complete a 1D bioreactor and validate its force output via a load cell as well as simulate its use via a cartilage surrogate/phantom (likely PDMS).

New Tasks

Task Name	Description and Concrete Outcome	Owner	Est. Time [hrs]
Request sample of bearing and shaft from Igus.	Ordered one bearing and 9-12in of hard-anodized aluminum square hollow shaft on a sample form available on Igus.com.	ST	0.5
Modifying CAD for prototype presentation	Added bearings, compressive interface PTFE, and VCAs to the CAD used for prototype fabrication.	ST	1
Finalize circuitry and mode of operation	Finalize the circuit and choose on either using the Arduino or MyDAQ	EL/JG	3
Force Sanity Check	Conducted finite element simulation of cartilage plug sample under loading conditions expected within the	GR	1.5

	bioreactor.		

Technical Section

Author: Sydney Therien
Editor: N/A

Request sample of bearing and shaft from Igus.	Ordered one bearing and 9-12in of hard-anodized aluminum square hollow shaft on a sample form available on Igus.	ST	0.5

After going to the Igus website to get information for filling out the order form, I noticed that there was a new "request sample" button on the page. I filled this out for one Drylin Q square flange and one for 9-12in of hard-anodized aluminum square hollow shaft. The total value of these products is about $70, so I'll watch my inbox for either a confirmation of shipment or a message that says this is too expensive to sample. If I don't hear anything from them by the end of spring break, I'm going to assume that my request won't be granted and I'll then fill out purchasing forms for these items.

After the prototype presentation, the team had a discussion about how we were going to finish out the semester. We've decided to validate our design and circuitry for one actuator and present our client with a working system rather than rush buying everything to build the design in its entirety. Ideally, we end the semester with a single actuator/bearing/plunger system that runs in a 3D print/¼" acrylic housing prototype. This housing will use the same acrylic panels as the current prototype, but the base and sample tray modules will be re-printed after some CAD modifications in a higher-quality biocompatible and autoclavable resin. The bioreactor could still be used for experiments in this state, but there would be many easy ways for the client to improve the device if she should choose to. If she wants to invest in the bioreactor fully, she could choose to hire the TeamLab to get the housing machined out of aluminum and order the other five units-worth of actuators, bearings, and shaft. The team is of the opinion that it would be more valuable to have a single working proof of concept that could then simply be multiplied than it would be to blow the entire budget in a rush to get a fully finished product.

Author: Sydney Therien
Editor: N/A

Modifying CAD for prototype presentation	Added bearings, compressive interface PTFE, and VCAs to the CAD used for prototype fabrication.	ST	1

To properly convey what the eventual design will look like, the CAD files used for fabrication of the prototype needed to be filled out with the rest of the design's components. This involved adding compressive interface PTFE cylinders, ThorLabs voice coils, and Igus Drylin Q flange bearings to the SolidWorks assembly. Photos were taken for the design review that split the device into its modules, which can be seen below.

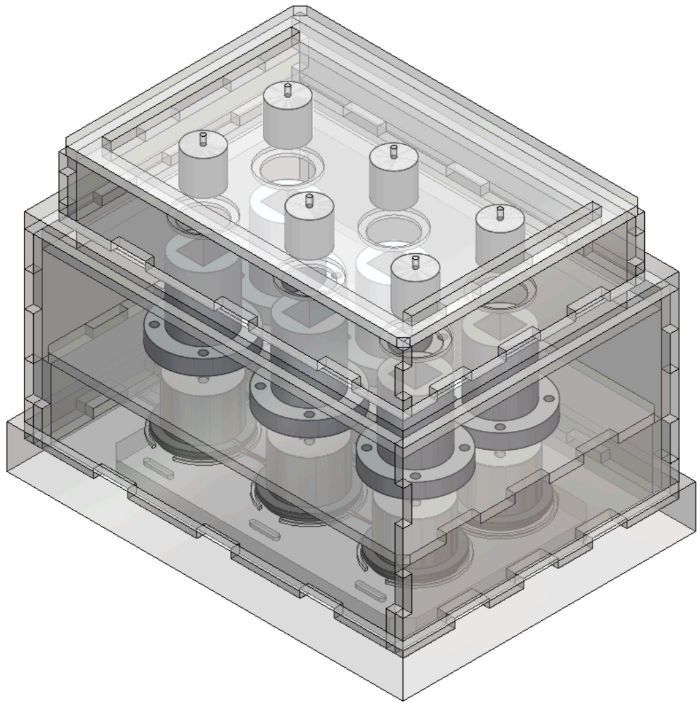


Figure 1: The full prototype in CAD complete with the purchased components.

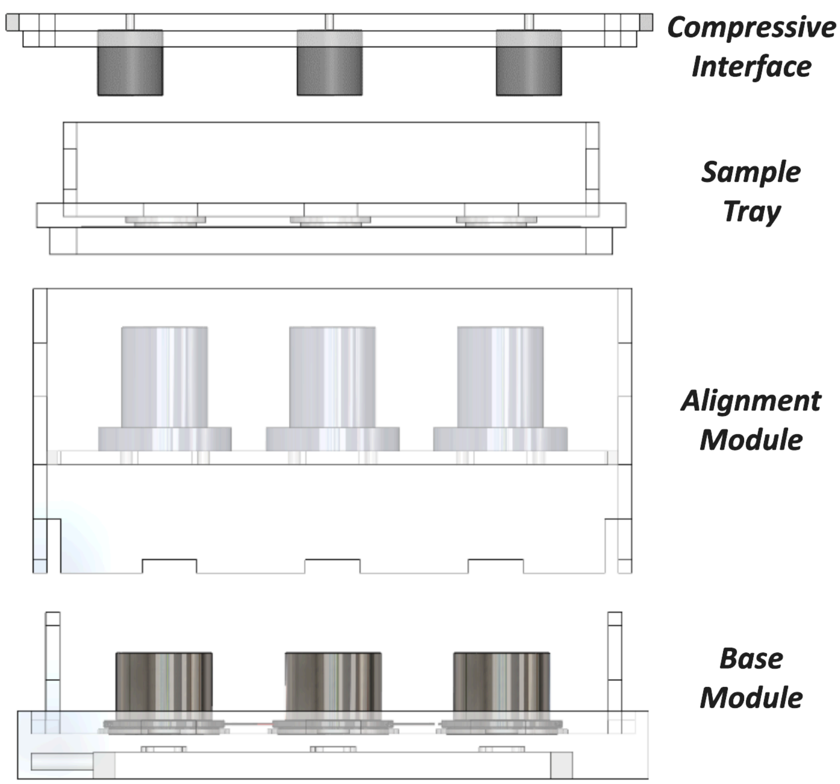


Figure 2: The labeled modular CAD of the prototype as it was presented.

Author: Emilio Lim
Editor: Jeffery Guo

Finalize circuitry and mode of operation	Finalize the circuit and choose on either using the Arduino or MyDAQ	EL/JG	3

We recorded some data from the MakerSpace using the MyDAQ and the Arduino. We found that when using the MyDAQ, the noise of 51dB from the Arduino due to the carrier frequency can be fully eliminated. When using the MyDAQ, we also found that the resulting voltage output across the VCA is a wave more similar to a square wave rather than a triangular wave. The voltage outputs when using the Arduino and MyDAQ are depicted below in Figures 3 and 4, respectively. To make the final decision, an overall summary was made to compare Arduino and MyDAQ using LabView.

After several discussions with Dr. Henak, we ultimately decided to use the MyDAQ instead of the Arduino which Dr. Henak has been supportive of. The circuit, however, will remain the same.

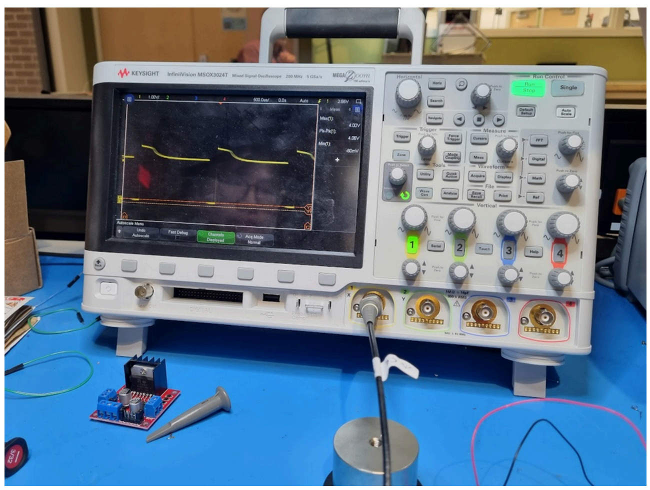


Figure 3: The voltage output across the VCA when using the Arduino to supply the input signal

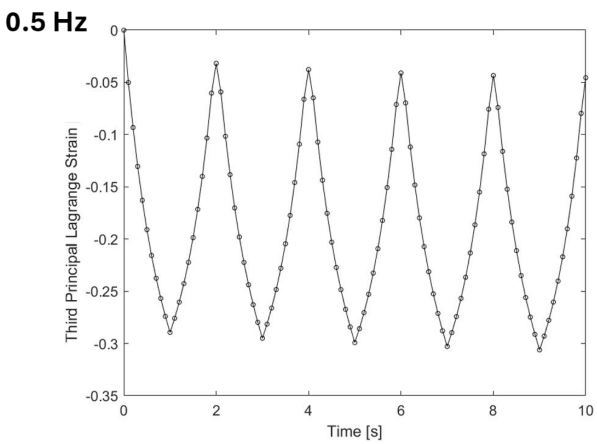
Figure 4: The voltage output across the VCA when using the MyDAQ to supply the input signal

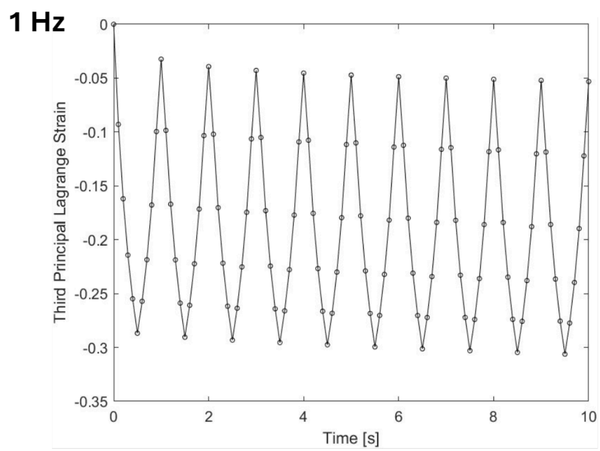
Author: Griffin Radtke

Editor: N/A

Force Sanity Check	Conducted finite element simulation of cartilage plug sample under loading conditions expected within the bioreactor.	GR	1.5

To ensure our initial force estimate (many, many weeks ago) was accurate to a more realistic model of articular cartilage, I ran a finite element simulation within FEBio of a ¼ symmetry cartilage plug (with our sample dimensions) via the biphasic solver, using properties previously discussed with Dr. Henak.With a triangular force input of -5.65 N (at 0.5 and 1 Hz) applied for 10 s, the third principal Lagrange strain was extracted and compared to our nominal ~-0.2 engineering strain approximation (showing alignment between our initial Hooke's Law approximation and our actual simulated output).





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
Individual Presentations					X										
Bioreactor Housing and Bearings															
Control with One VCA								X							
Working Prototype										O					O

Full Bioreactor CAD Model				X											
Fabricated Bioreactor									X						
Circuitry with All Six VCAs															
Final Review										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

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
Finalize prototype CAD and manufacture prototype parts	Put finishing touches on the actual 3D model and create SolidWorks drawings that can be laser cut. Use Makerspace facilities to 3D print and laser cut the parts for the prototype.	ST	3
Prepare presentation for prototype demonstration	Administrative – working to concisely present physical and analytical work.	All	2+
Continue developing working electronics/circuitry	Continue developing the circuit and electronics to operate the VCA	JG/EL	2
Draw a circuit diagram	Use LTSpice to draw out the circuit diagram	EL	0.25
Temp. Analysis of Compressive Lid	Verified acrylic's stability under thermal expansion at incubator-like conditions.	GR	1.5

Previous Work

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 Ff = mu*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.

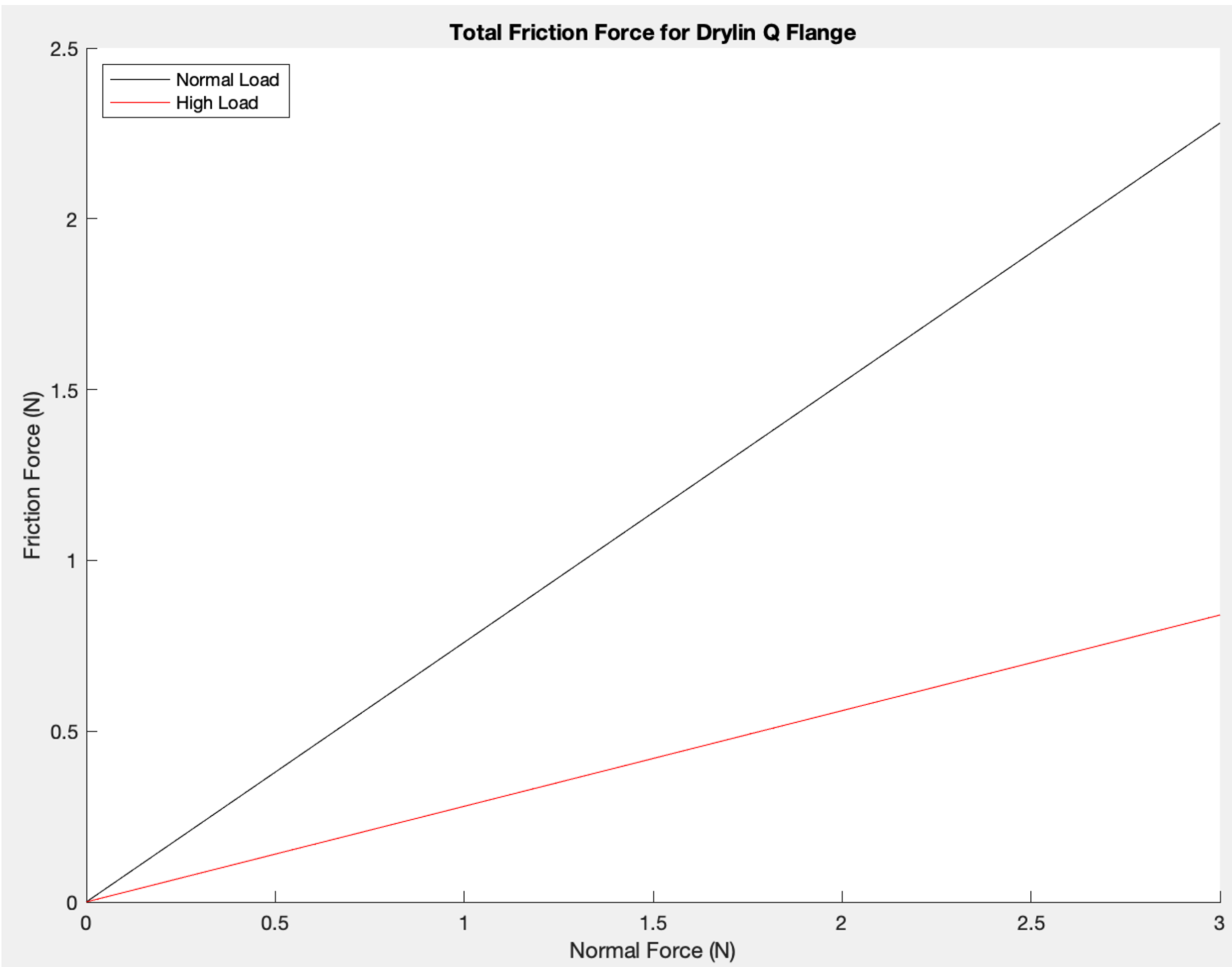


Figure 1: Plot describing the total friction force opposing actuator output force for the Drylin Q flange bearing over a range of normal forces.

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 um/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.

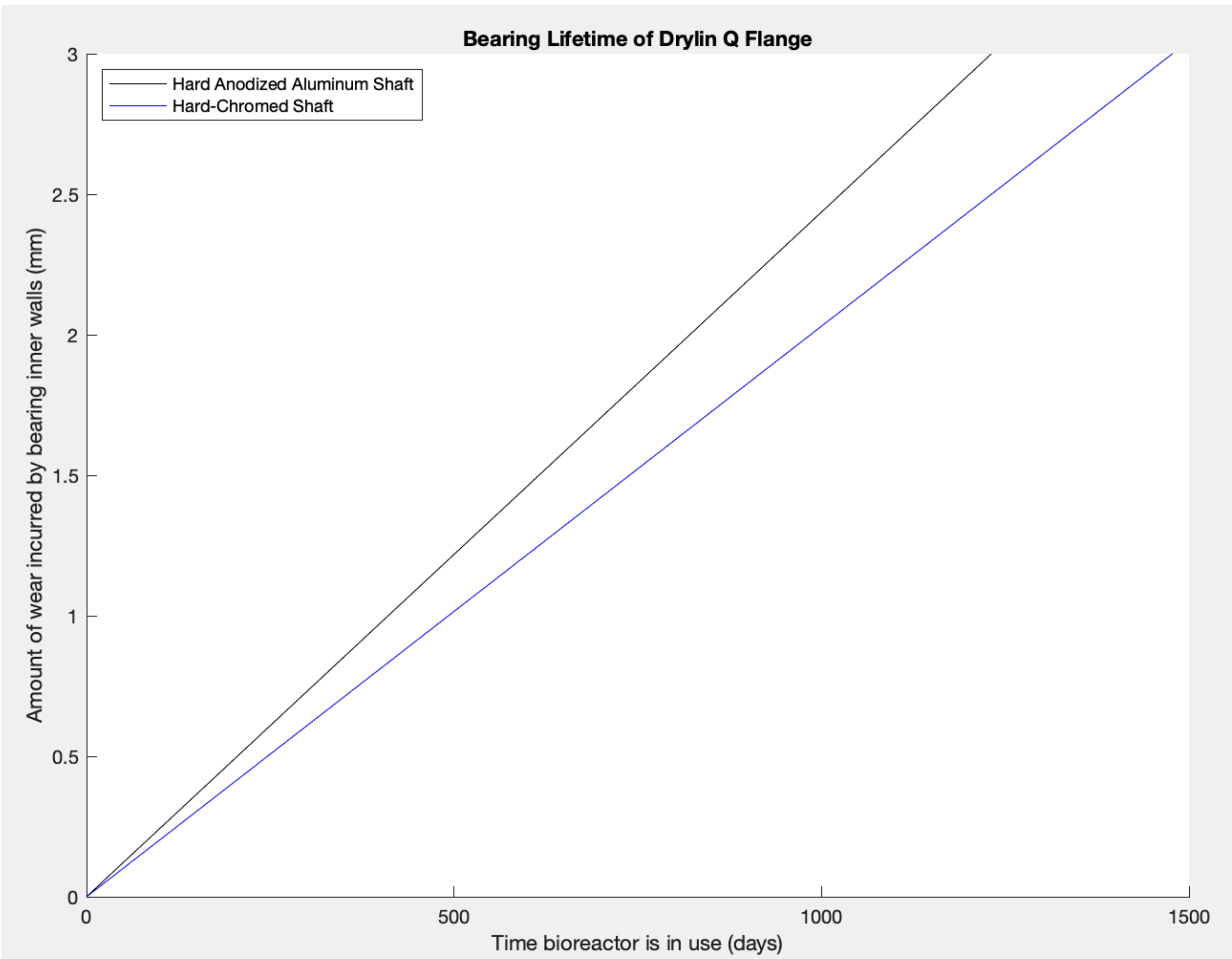


Figure 2: Plot describing how long the bioreactor is in continuous operation versus how much that operation wears down the walls made of gliding material.

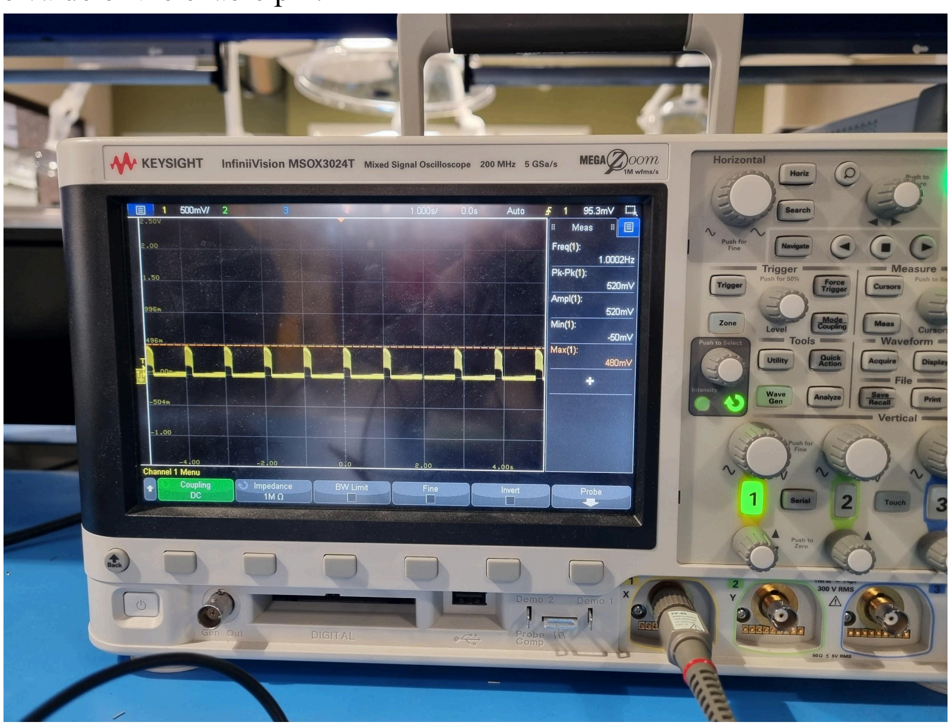
What Figures 1 and 2 show is that the Drylin bearings have a much longer life than previously thought and seem to be a fitting bearing for the bioreactor. With this information, I hope that the team can be more confident moving forward with incorporating them into the design. I also sent igus an email 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 testing H-bridge	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 CAD for Machining	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).

Author: Sydney Therien
Editor: N/A

Finalize prototype CAD	Put finishing touches on the actual 3D model and create SolidWorks drawings that can be laser cut.	ST	2

In preparation for the upcoming prototype presentation, the CAD model that had been created based on TeamLab manufacturability feedback had to be finalized and converted into a file type that could be manufactured. This involved first making sure that everything fit together in the SolidWorks parts assembly and that there wasn't any overlap of pieces hiding anywhere, as well as making sure the design itself was 100% good to print/cut. Then, a SolidWorks drawing was made of the pane pieces that will make up the box walls. This was done in such a way that the tongues and grooves fit into each other as much as possible to save space on the acrylic sheet.

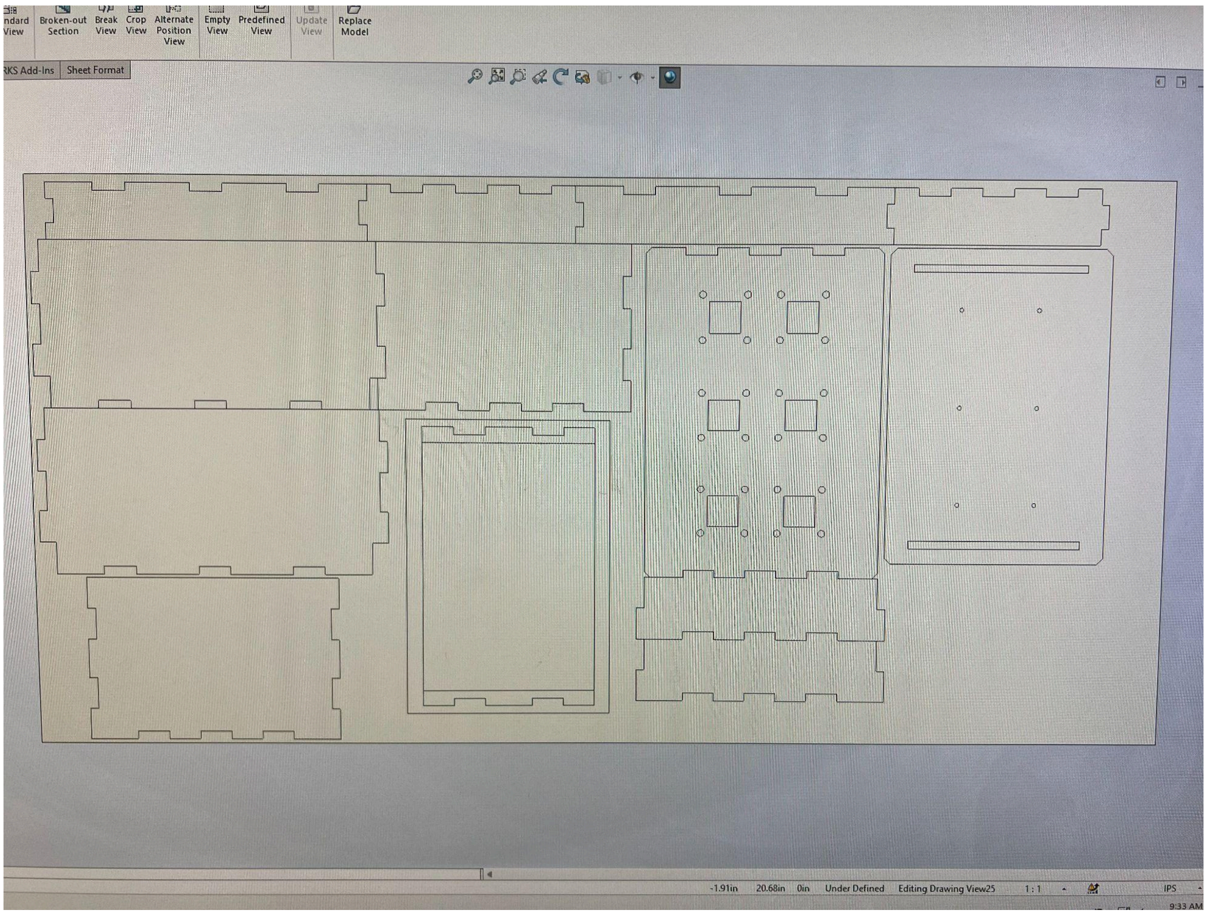


Figure 1: A picture of the computer screen that had the final SolidWorks drawing.

The file shown in Figure 1 was then converted to .dxf and cut on a 24x36 in clear acrylic sheet that is ¼" thick purchased at the Makerspace for $36.50. There were no problems with the cut, the pieces were to scale, and it fit together well.

Figure 2: Testing the tongues and grooves of the cut acrylic pieces to see how they fit together (no adhesive has been used yet).

The 3D printed parts, the base and the sample tray, are both printing currently. They should be done by the end of today (Friday 3/15). They were printed with white PLA with 20% infill on the tray and 10% infill on the base (to save money). The print cost was $41.35, with the base costing $23.30 and the tray costing $18.05. This brings the total cost of this prototype to **$77.85** including the acrylic. Once the base and tray are finished printing, the paper will come off the acrylic pieces and the prototype can be assembled. It will make its debut on Monday at the next client meeting!

Author: Jeffery Guo
Editor: Emilio Lim

Continue developing working electronics/circuitry	Continue developing the circuit and electronics to operate the VCA	JG/EL	2

Over this past week, Jeffery and Emilio continued to work on developing the appropriate circuitry to operate the VCA. **We created a circuit capable of supplying a triangle wave to**

operate the VCA at 1 Hz. With the input of Makerspace staff, we decided to use an N-channelMOSFET instead of an H-bridge, because H-bridges are better suited for applications requiring bidirectional actuation, which we do not require, so an N-channel MOSFET would be better for our case. We purchased the [Infineon IRFZ44N], at an affordable price of $1.00 from the Makerspace, which can handle the voltages and currents required to operate the VCAs.

In summary, the circuit we developed (with the wonderful help of friendly Makerspace staff), depicted in Figure 3 below, works by receiving a PWM triangular input signal at the desired frequency (i.e., 1 Hz) from an Arduino and an input voltage from a power supply. The circuit also contains a diode and resistors which function to protect various components such as the MOSFET. The force output is controlled by adjusting the power supply's voltage. The maximum current the VCA drew was roughly 700 mA. Video documentation of our functional circuit and VCA is available **here**.

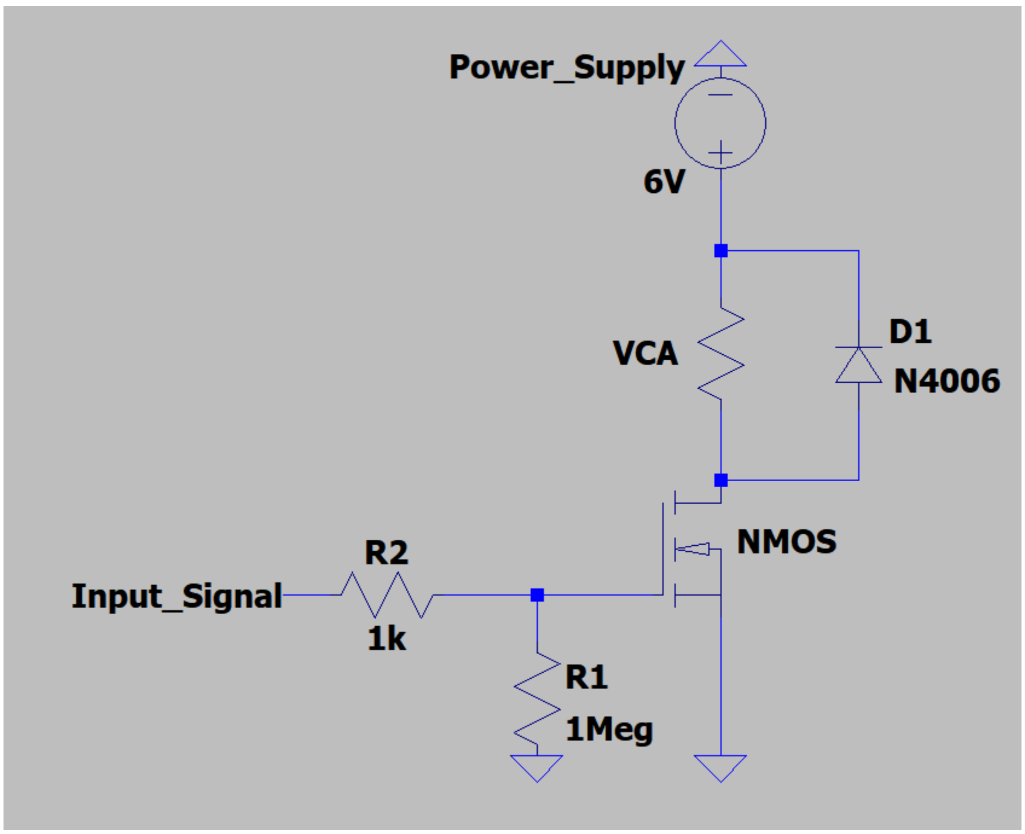


Figure 3: Circuit schematic.

For our next steps, we will look to test our circuit using a NI DAQ/myDAQ in place of an Arduino to provide the input signal. We will also need to verify sufficient force output using our newly developed circuit and develop a calibration curve of power supply voltage vs. force applied. With the prototype bioreactor housing nearly complete, we're also excited to see how the VCA(s) will physically fit and sit securely in the housing. Soon, whenever appropriate, we'll look to purchase the last five VCAs and the additional circuit components we need to control all

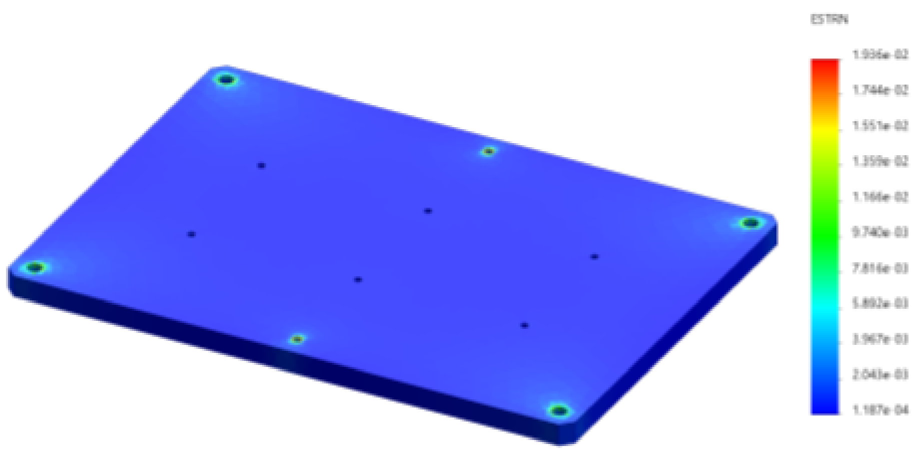
VCAs. With this in mind, we will also find and purchase a power supply capable of supplying enough current to power all 6 VCAs, roughly 6-7 A maximum.

Author: Griffin Radtke

Editor: N/A

Temp. Analysis of Compressive Lid	Verified acrylic's stability under thermal expansion at incubator-like conditions.	GR	1.5

As discussed in prior reports, the final design will almost certainly rely on a 10 [mm]-thick laser-cut acrylic lid structure to 'deliver' the compressive load. While the loading itself has been simulated, with no risk of failure (i.e., ~4x F.O.S. calculated), temperature has yet to be analyzed; although, intuitively, little-to-no warping is expected *within the lid* as a result of the temperature increase (i.e., to 37C) to incubator conditions, verification, analysis of strain is obviously necessary as a final proof.



Thermal simulation results, with strain analyzed to verify minimal deflections with a Δ=15 [C]. Strain is minimal within the bulk of the material, although potential singularities arising from the mesh exist about the bolt locations.