Improving the Design of a Soft-body Robotic Swimmer

Bruke Baraki
Herbert J. and Selma W. Bernstein Class of 1945 Internship Report
Mechanical Engineering and Applied Mechanics
University of Pennsylvania

Abstract

The main objective of the project is to improve the design of a soft-body robotic swimmer. The mechanism of the robot uses a magic ball origami pattern, which emulates the movement of many cephalopods. By moving between a cylindrical and spherical state, the robot can intake and outtake water for propulsion. However, the first generation prototype has a few issues that negatively affects its performance. The aspects of the swimmer that were investigated includes:

- The fishing line that compresses the skin.
- The end caps that hold the swimmer together.
- The origami skin pattern.

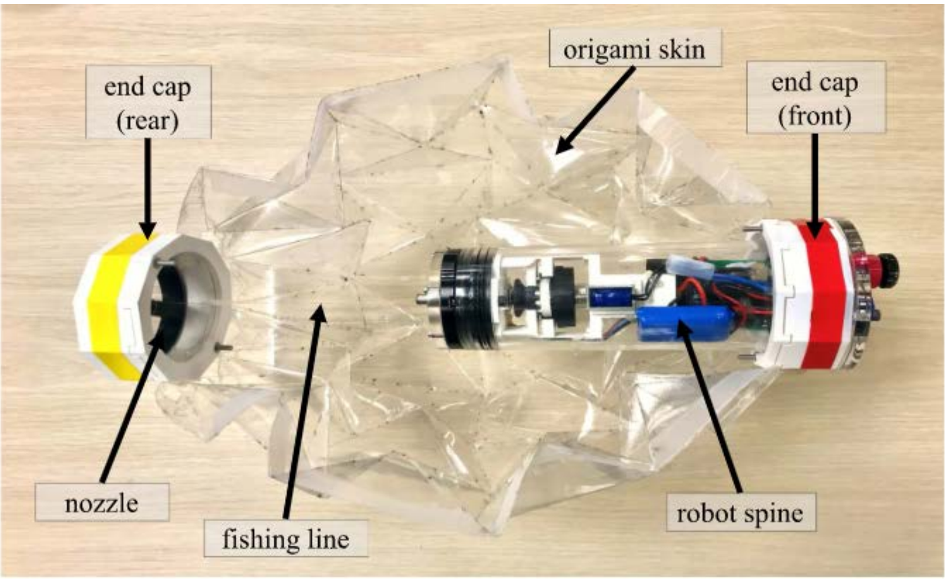


Figure 1: Diagram of First Generation Design
Source: Origami-Inspired Robot That Swims via Jet Propulsion[1]

Improving the Fishing Line

The fishing line compresses the skin to create propulsion. After a few cycles, due to the force applied on the line, the line experiences a certain amount of stretching. This stretching causes the swimmer to be less efficient since there is less compression each cycle. If there is less compression, the swimmer can not intake as much water as it should, which results in less propulsion. Not to mention that the line must be switched out frequently in order to combat this. In this section, several types of lines that vary in material type (ex. monofilament, fluorocarbon, braid) and thickness (ex. 10lb.- 80lb.) were tested. The goal was to apply a certain load on the line and observe its stretching behavior.

20lb fluorocarbon was used on the swimmer originally. The stainless steel line and 65lb braid seemed to be the most appropriate for the application since they have a diameter close to 0.4mm (the diameter of the O-ring, which keeps water from leaking into the robot spine).

---

[1] Yang, Z., Chen, D., J. Levine, D., & Sung, C. (2021). Origami-Inspired Robot That Swims via Jet Propulsion. *IEEE Robotics and Automation Letters*, *6*(4), p. 7146, II. https://doi.org/10.1109/LRA.2021.3097757

Determining Friction

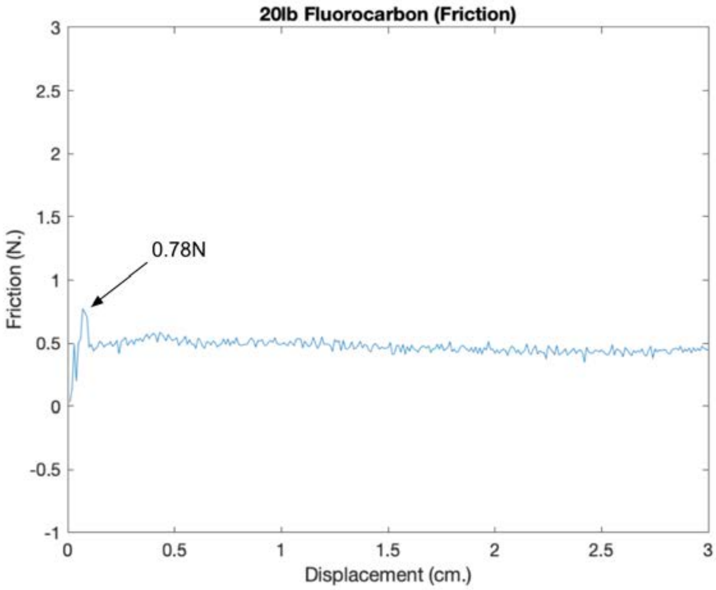
In order to determine the total load to apply on the line, the kinetic friction between the line sample and actuation mechanism has to be measured using an MTS machine. The actuation system was attached to the bottom grip. One end of the line sample was wrapped around the spool and the other was attached to the top grip. To start testing, the TW Elite application was launched on the desktop next to the MTS machine. The template called MTS EM Tension was selected. On the pretest screen, the initial speed was set to be 10 mm/s. The friction acts on one end of the line and the line exerts a tension force on the MTS machine. Since the system is in equilibrium, the tension force equals the friction force on the bottom of the line.

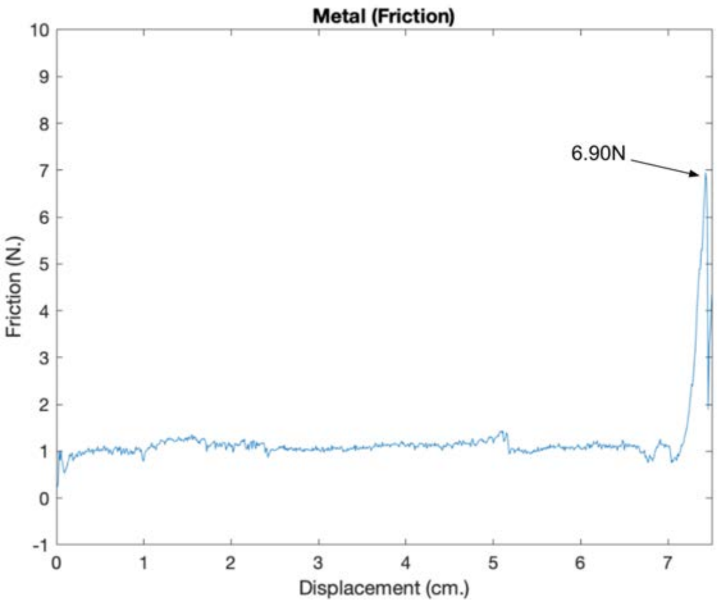
$$F_{MTS} = F_{fr}$$

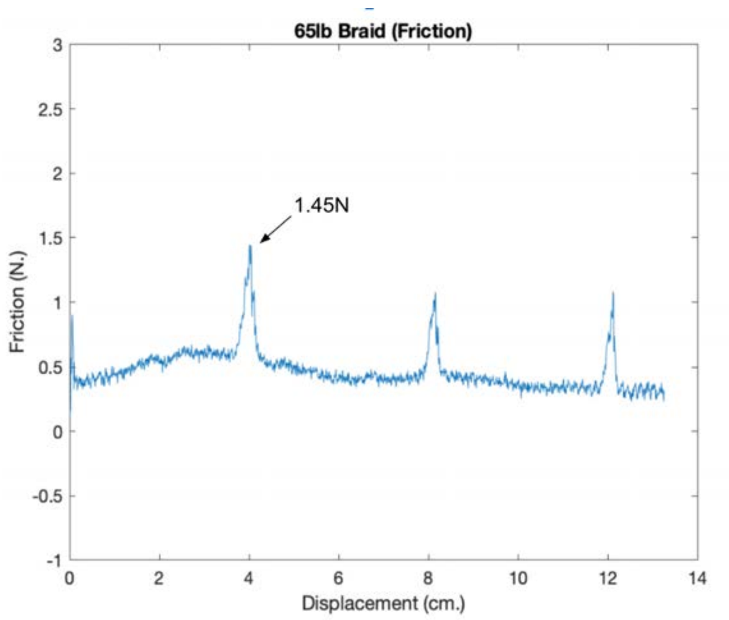
All other settings in the pretest were insignificant. The stop condition was done manually: stop the test when a majority of the line has been released from the spool. Before any testing transpired, the MTS machine had to do a verification check, which compares device readings from actual calibration to the readings recorded during the check to identify problems with the machine. Nothing should be on the grips when this happens. When the actuation system was attached to the grips, the load measured by the machine was the force due to gravity, which was zeroed at this point.

After the preliminary steps had been completed, the start button was pressed. The top grip started to move upwards. The stop button was pressed to stop the grip before the spool ran out of line. The software automatically plotted the displacement vs. force data.

MTS Data:







	Max Friction(N)	Total Load on Line(N)
20lb Fluorocarbon (control)	0.78	20.78
65lb Braid	1.45	21.45
Metal Line	6.9	26.9

Data Analysis

The maximum friction refers to the highest data point in the displacement vs. friction plot, as shown in plots with the arrows. The total force applied on the line equals the friction between the line and actuation system plus 20N [2]. The metal line displacement curve looks atypical compared to the other two since it unwound itself during the test. A similar behavior was found during the swimmings tests at PERCH. The friction force from all the samples, as expected, was small compared to the force from the motor.

Determining Stretchiness

Now that the friction has been determined, enough information has been gathered to experiment on the stretchiness of the fishing line samples. In the interest of emulating the line being stretched while swimming, an experiment was conducted to replicate this behavior. A custom template named MTS_Multicycle_timeinput was used, which does the following steps:

- The specimen extends at 10 mm/s until the load equals 20N + friction.
- Hold it for 5 sec. (approximately equal to the duration of skin compression[3]).
- Release the specimen until the crosshead equals 0mm.
- Repeat 10 times.

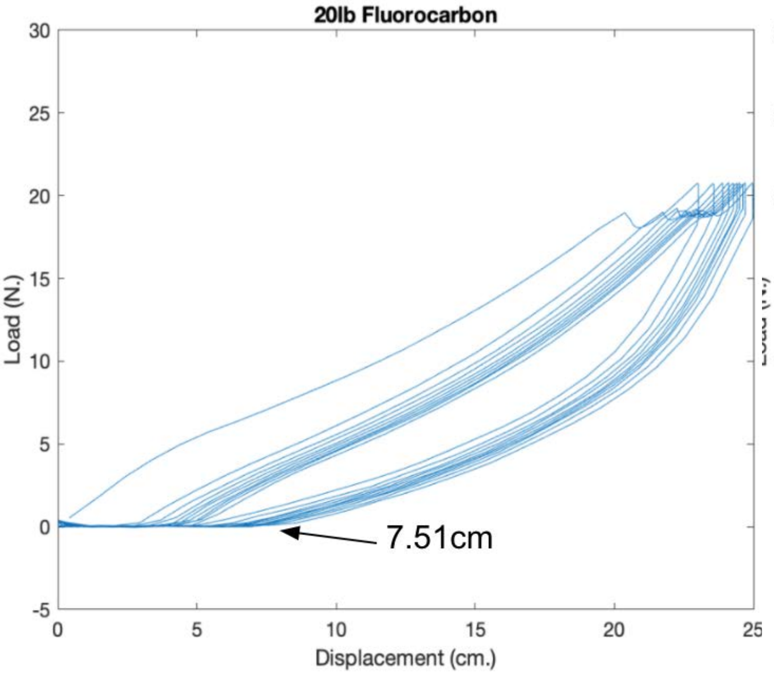
The sample was attached to the top and bottom grip, as shown *on the right.* The signals were verified and zeroed in the same manner as described in the friction section. In the pretest screen, the initial speed was set to 10 mm/s and the force end point 1 was set to be (20 + friction)N. The number of cycles were set to be 10. All other settings were not important. The start button was pressed. When complete, it was returned to zero. The data was exported and plotted using MATLAB.

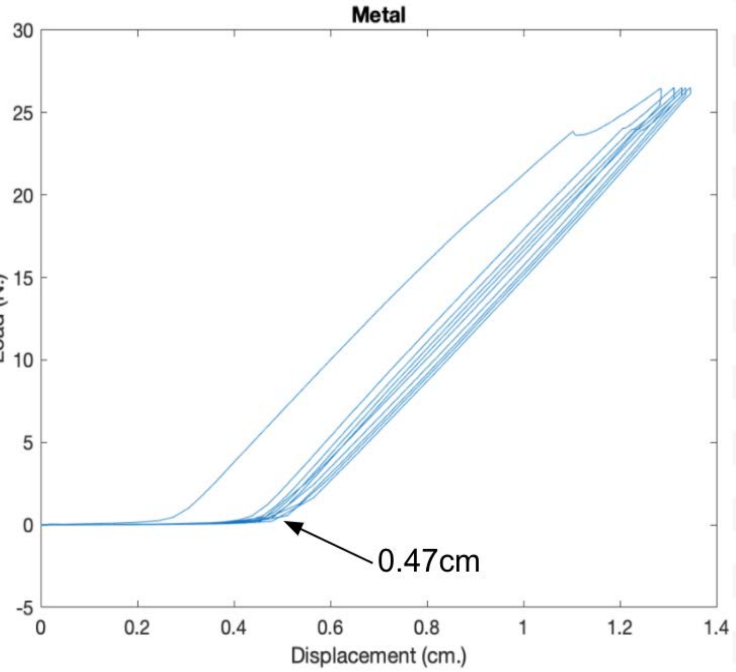
MTS Data:

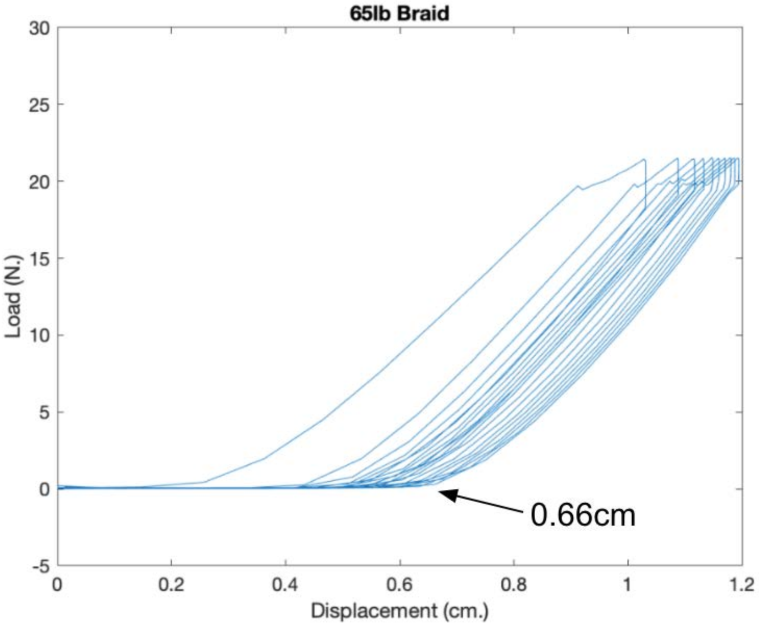
---

[2] Origami-Inspired Robot That Swims via Jet Propulsion, p. 7148, III., B. Fabrication

[3] Origami-Inspired Robot That Swims via Jet Propulsion, p. 7149, V., A. Trajectory Analysis







Line	Amount Stretched (cm.)
20lb Fluorocarbon	7.51
65lb Braid	0.66
Metal	0.47

Data Analysis

When the line was extended and released, the displacement vs. load curve converged as the cycles increased. The amount stretched was determined to be the largest displacement of the crosshead when the load was reasonably close to 0N (anything less than 0.2N was considered reasonable). This was indicated by the arrows in the plots. As expected, the fluorocarbon experienced a significant amount of stretching compared to the two other samples.

Conclusion

Although the MTS results for the metal line predicts little stretching, further experimentation has found the opposite. The metal line was elongated after water tank tests at PERCH. The best explanation was the knot's moving and shifting as the line did work. Also since the line was quite firm, it would unravel itself in the spool as discussed in the friction section. On the other hand, the 65lb braid has similar

MTS results, but is more pliable and the knots do not move. Tests at PERCH using the 65lb braid have found it to be suitable for the application since it did not have any unexpected behaviors, like the metal line.

Redesigning the End Caps

Introduction

The end caps, as shown in *Figure 1,* are responsible for connecting the fishing line to the skin. However, the original prototype had 3 specific issues:

Issues with previous design

Issue 1: The polygonal design (Interchangeability)

- The polygonal design of the end caps, as shown in *Figure 2*, does not allow for the interchangeability of the skins that are attached to it. For instance, a 4x10 skin would need a ring with 10 sides and the end cap would also need 10 sides.
    - Solution: By using a circular design, as shown in *Figure 3*, the end cap can be used independently of the dimension of the ring and skin.

Figure 2: Rear End Cap (Before)

Figure 3: Rear End Cap (After)

Issue 2: Water leakage through gaps

- Originally, the tabs of the skin were attached horizontally to the end caps. Since there are gaps between the tabs, water could leak through.
    - Solution: With the vertical attachment, the tabs are pulled during assembly so that gaps are minimized.
    - Note: This was also fixed by lowering the length of the tabs of the origami skin later on during the summer.

Issue 3: Easiness of reassembly

- Originally, the inner cylinder, or robot spine, can only be removed through one side of the swimmer because the inner diameter of the rear end cap in *Figures 1 and 2* was too small.
- The line also had to be cut every time the inner cylinder had to be removed because it was tied to the nozzle (the black piece in *Figure 2)*, which was screwed to the end cap.

  - Solution: The rear end cap has the same diameter as the front end cap, and the removable rod allows the inner cylinder to be removed through both sides easily. Since the knots are made around a rod, the line can be removed without cutting.

Fabrication Process

The fabrication process for the end caps involves making designs in Solidworks. These designs were 3D printed. It is recommended to use a 40% infill and 2 shells. Since they are rather large in size, it is recommended to use the Fortus printer located at AddLab or PERCH. After fabrication, the rear end cap should look like *Figure 3*. The rear and front end cap for the new design are identical except for the rod in the middle.

Redesigning the Origami Skin

Introduction

The magic ball design allows the skin to switch between a high volume state (spherical) and a low volume state (cylinder). They are composed of rows and columns as shown in *Figure 4*. The 4x10 skin is most commonly used in experimentation since it is equal to 2.5 in their column to row ratio. (10:4 = 2.5). The second most commonly used skin is the 6x15 skin, which also has a 2.5 ratio (15:6 = 2.5). However, a 6x15 skin has an odd number of columns making its fabrication slightly different from a 4x10. A 2.5 ratio is ideal for the magic ball based on previous papers and experimentation[4]. The following section will describe the new modifications for the origami pattern.

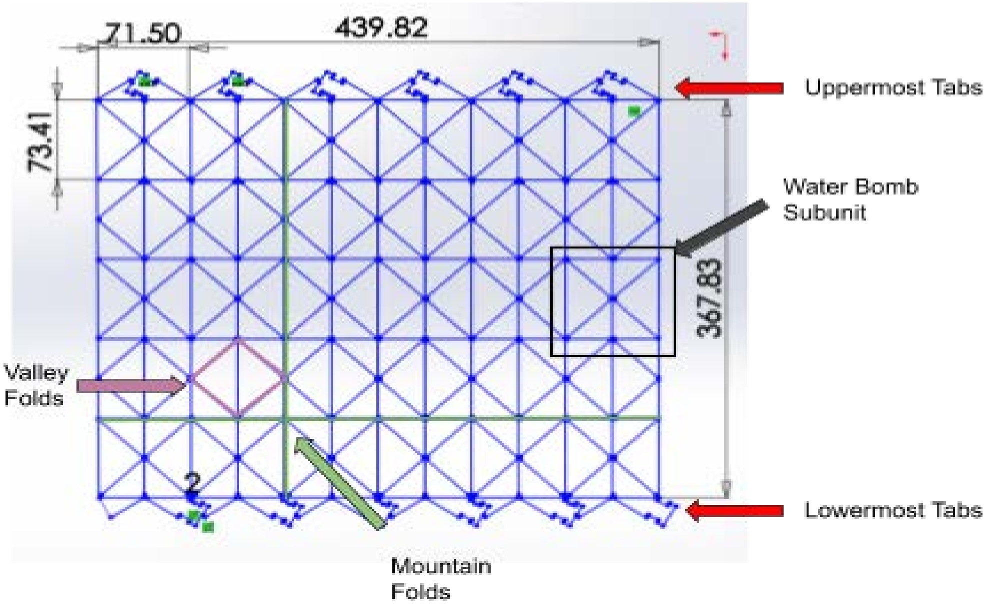


Figure 4: Hole Arrangement for 4x10

Issues with previous design

Issue 1: Long tabs

- The tab length, as shown in *Figure 5*, causes gaps when the skin is attached to the acrylic ring. Water would leak, which would negatively affect the swimmer's efficiency.

---

[4] Origami-Inspired Robot That Swims via Jet Propulsion, p. 7147, III

- Solution: Make the length of the tabs equal to the thickness of the ring (0.125' or 3.175mm), as shown in *Figure 6*.

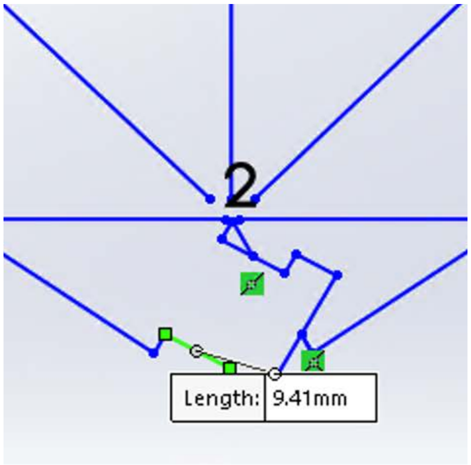


Figure 5: Origami Tabs (Before)

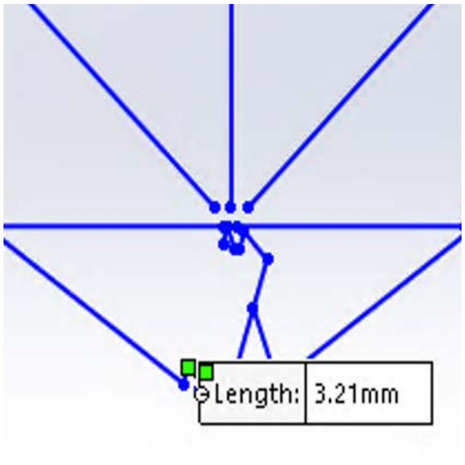


Figure 6: Origami Tabs (After)

Issue 2: Distortion on pattern

- Distortions on corners of the origami skin negatively affect its longevity.
- Solution: Holes were placed on the vertices to lower stress. Circles with a 2mm diameter, as shown in *Figures 7 and 8,* which are an example of a 6x15 pattern, were placed in the following configuration. The same is true for 4x10 skins. 5x12 skins are peculiar since they have an odd number of rows. This requires more research to figure out a solution for that instance.

Fabrication Process

Two 0.004" thick sheets of mylar were cut from a roll. The sheets were roughly larger than a laser-cut skin but small enough to fit into the laser printers at the RPL since laser printing is a subtractive process. A 4x10 uses only one .dwg, while 6x15 uses 2 different .dwg files. This is because each sheet has 7.5 columns. In order for them to line up, the second sheet has to be shifted by half a column.

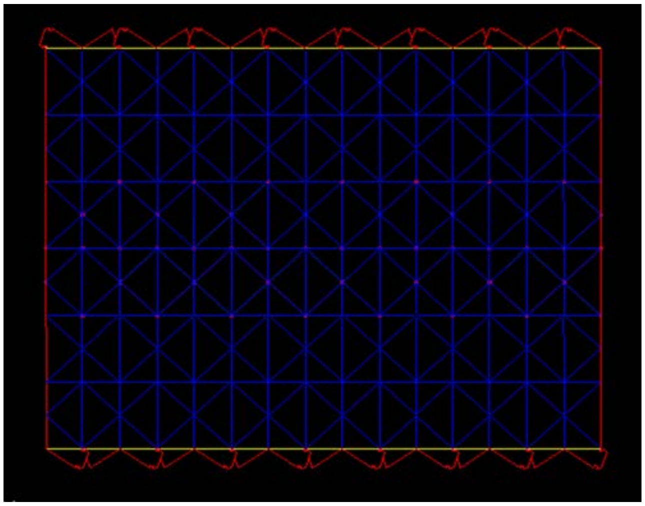


Figure 7: 6x15 pt.1

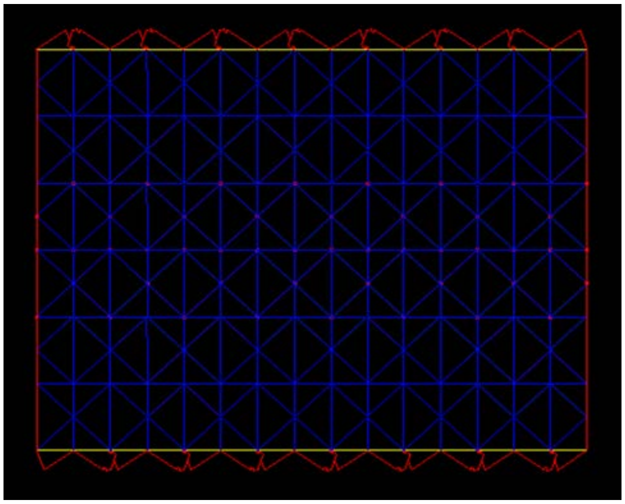


Figure 8: 6x15 pt.2

After the .dwg files were loaded into DraftSight, it was exported to the laser printing software. Before printing, this .las file was imported into the software. This file loads in the laser speed, power, and ppi setting for all the colors used. The following are the settings for the colors:

Color	Power	Speed	PPI	Z-axis	Flow
Red	6%	6%	1000	Off	100%
Yellow	0.5%	10%	75	Off	100%
Blue	6%	6%	23	Off	100%

The laser printer was calibrated before use, using the calibration tool located next to the printers. It was placed on the bed and the bed was moved upwards until there was a slight movement of the tool. The 0.004" thick mylar sheet was inserted into the printer. The laser head was moved to the uppermost, lowermost, easternmost, and westernmost point of the print to ensure that the print fits the sheet. The start button was pressed. This was repeated with the 2nd .dwg file. The procedure described in my spring 2021 report was used in folding the pattern. Although a 4x10 skin was folded in that report, the process is identical, but takes longer.

Future Considerations

Over the course of the summer, we successfully found and tested a more appropriate fishing line sample. This is due to the little stretching and lack of abnormal behaviors.The same could be said for the end caps and origami skin; however, the origami pattern, especially the 5x12 version, may receive new modifications in the future, such as different sized holes and different shapes for the holes, to further lower stress concentrations. The end caps may receive more modifications if needed. During the fall 2021 semester, I plan on continuing this research, focusing on the circuitry and continuing fabrication.

I would like to thank the members of the swimmer group, Dr. Sung, and the mechanical engineering department at Penn for guiding and giving me the opportunity to do research this summer.