Robotic Systems Mini Project: Fluid Actuated Fish Tail

Everardo Gonzalez

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Abstract

My project explored the concept of a soft robotic tail made of EcoFlex that was actuated via pressurizing half of the tail while depressurizing the other half of the tail. This exploration was heavily inspired by SoFi, a soft robotic fish from MIT CSAIL [1], and Pnuenets from the Soft Robotics Toolkit [2]. I successfully created and tested two unique EcoFlex tails, but both fell short of performing as effectively as SoFi's tail. While I began my exploration of fluid based actuation with pnuematics, I quickly moved to hydraulics as I found the buoyancy of a pneumatic tail difficult to control. The first tail was effective when powered pneumatically, but thin tubing made it extremely slow when powered hydraulically. I created a second tail specifically designed for ease of use with hydraulics, but overcompensated for the first tail's problems, and made the second tail ineffective as an actuator.

1 Project Description

The goal of this project was to build a semi-biomimetic soft fish tail that could sway side to side via fluid transfer between chambers on either side of the tail. My tail designs were heavily inspired by SoFi, from MIT CSAIL [1], and the Pnuenets from the Soft Robotics Toolkit [2]. I hoped that by meshing together the concept of a soft fish tail from SoFi with the ribbed design from the Pnuenets, it might be possible to create a relatively small, but effective fish tail.

2 Learning Goals

I had specific goals for what I wanted to learn when working on this project.

1. Learn how to design a fish-shaped robot
2. Learn how to design and fabricate custom and complex parts out of EcoFlex
3. Gain a stronger intuition for working with EcoFlex in general

3 Design

3.1 Tail 1

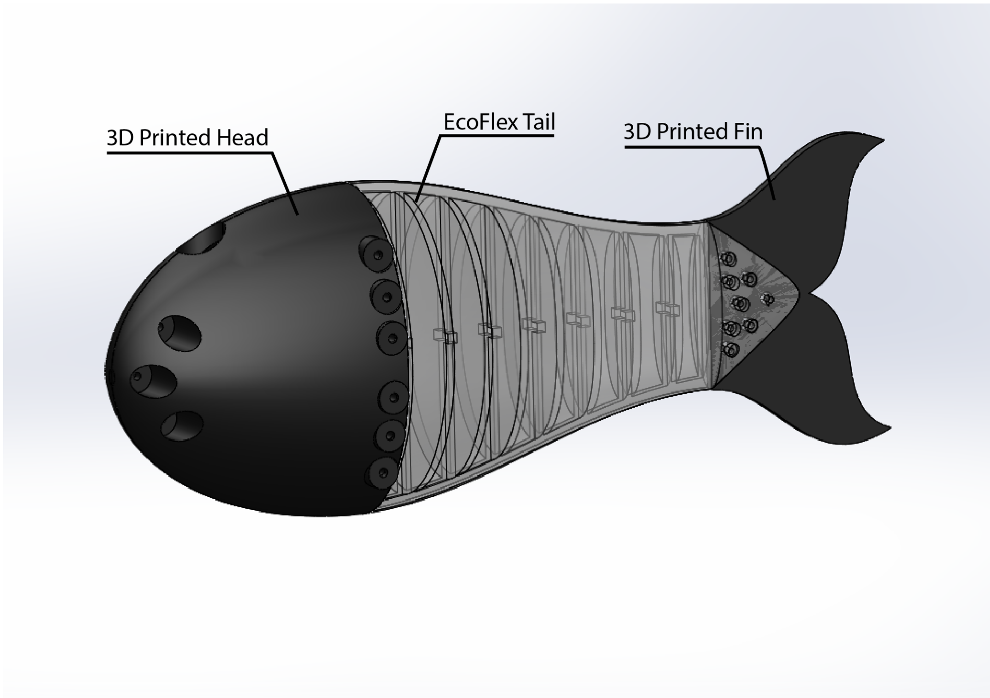

Figure 1: This is the overall design of the first fish, with its primary components labelled. The head and fin for the fish are made of rigid plastic, but the tail is made of soft silicone. This means the center of the fish can bend while the head and fin remain rigid.

Figure 1 shows the overall design of the first fish in Solidworks. I started by roughly approximating a fish shape from images of fish online, and broke that shape up into three primary components: the head, the tail, and the fin. The head was split into two pieces that were mounted together via screws towards the front of the fish head. To mount to the tail, the head is screwed into a flange from the tail that slots into the head pieces. The fin is similarly screwed into the end of the tail to keep it fixed to the tail. There is also a hole near the top of the head that makes it possible to route tubing into the fish to actuate its tail.

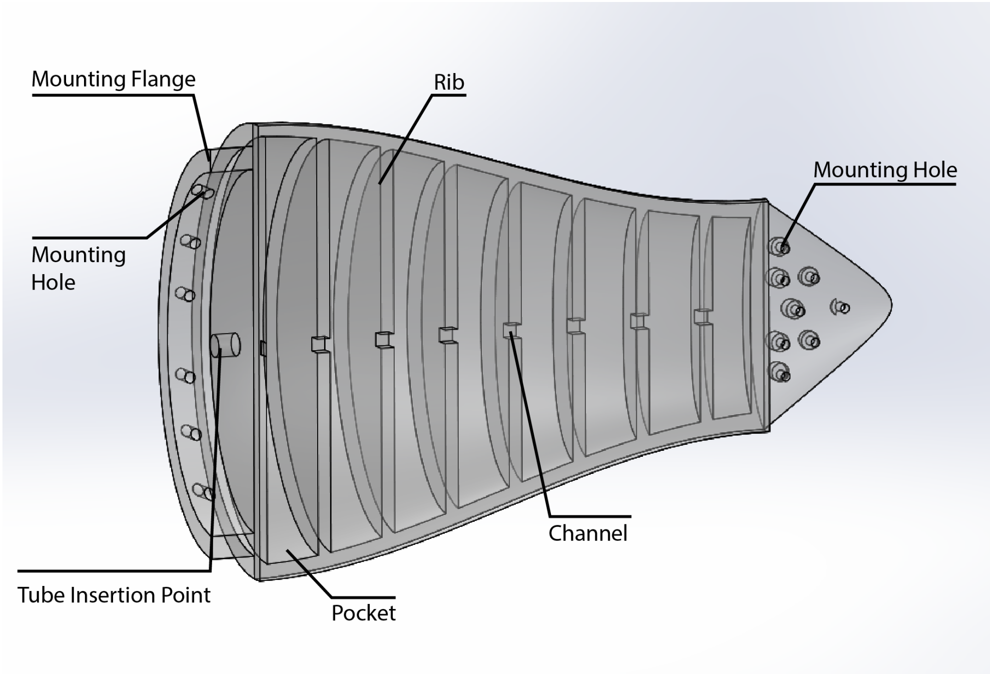

Figure 2: This is the isolated tail of the fish. All terminology for refferring to the different parts of the fish tail are labelled here for convenience. We can see that the tail resembles a Pnuenet mold, but overall seems more hydrodynamic.

We take a closer look at the tail in Figure 2. The overall tail is one of the chambers of the fish. This tail has pockets that are relatively wide compared to its ribs, and a small channel for fluid to move between the different pockets. Not pictured is a rigid piece that would be fixed into the flat side of the tail. This rigid piece will make it so that when the chamber is pressurized, the pressure pushing inwards towards the rigid piece will make the rigid piece curve. It's interesting to note that the overall design resembles SoFi's tail, but with some key differences. This tail seems to have much wider pockets, less ribs, and a smaller channel. Additionally, this tail lacks an outlet for initial priming. Initially, I didn't consider the implications of these design decisions, instead focusing on creating a simple design that would be easiest to manufacture. This tail was intended to be a trail run of whether I would even be able to replicate SoFi's motion.

The channel is much more similar to a Pnuenet than to SoFi's channel as I already had experience with that channel size and shape, making me more confident that I could make it work. By using less ribs, I took away additional points of failure and reduced the complexity for manufacturing this tail. The wider pockets were also a nod to the Pnuenets, as they typically have wide pockets compared to their ribs. I chose not to include an outlet for initial priming because I did not see the need for it, and didn't want to risk creating a leak in the tail.

3.2 Tail 2

I designed the second tail only after testing the first tail and finding its shortcomings. I primarily designed the second tail around three shortcomings of the first tail. The first was that it was difficult to fill the chamber with water for testing hydraulic actuation. The second was that once it was filled with water, it was difficult to pressurize and depressurize the chamber through the thin tubing that interfaced with its insertion point. The third was that it was nearly impossible to keep the tail from pulling its mounting flange partly out of the head. I also tweaked the design in a few ways I thought would yield a more effective tail.

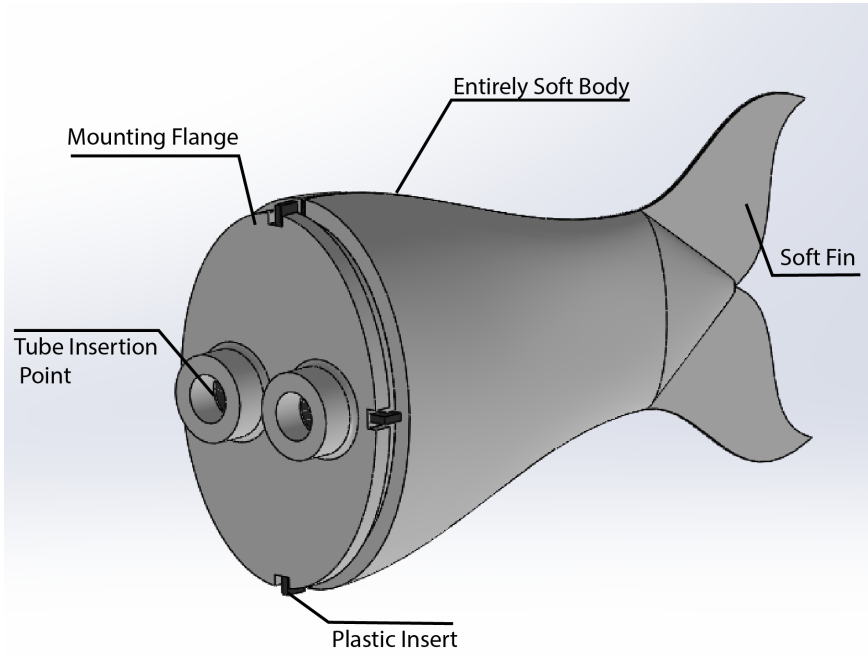

Figure 3: This shows the overall design of the second fish tail. In this design, the tail and the fin are combined into one part. Labels define terms used to reference parts of this tail.

We can see the overall design in Figure 3. I did not include a head for this design because I was focused more on the tail, and didn't want to slow down the tail design by including a head. One of the biggest changes I made was turning the tail and fin into a single, soft part. The tail still has a rigid piece of cardstock between the two chambers, but it extends all the way to the fin, as the fin is no longer a separate 3D printed part. I did this to mimic SoFi's design more closely in the hopes that it would make the tail easier to bend. In the figure, we can also see that the tube insertion point has gotten much bigger. I designed this tail to work with larger tubes so that water would move in and out of the chambers with less resistance. The mounting flange has also become more complex, both in shape, and in the addition of a plastic insert. This was also to mimic SoFi's design more closely. I hoped that this redesigned flange would make it easier to fix the tail to either a head or a test stand, but due to time constraints, I didn't get to test it.

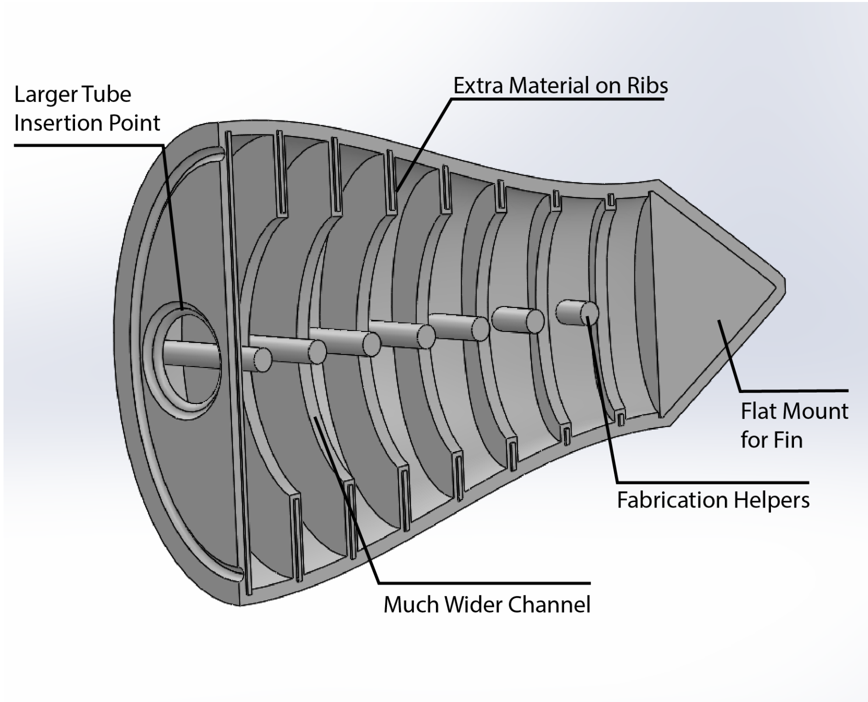

Figure 4: This is a close-up of a chamber for the second fish tail with labels calling out significant changes.

In Figure 4, we take a closer look at the redesigned chamber. There are some cylinders that run across the center of the tail, but these are simply to help with manufacturing. They are removed once the tail is molded. We can also see that the ribs have some extra material where they attach to the flat, rigid piece. This was to help with ensuring the spacing for the rigid piece was correct. In the back of the tail, we see that there are no longer screws to mount this chamber to the fin, as the fin will now be sealed directly onto the chamber with silicone. The mounting flange is no longer part of the chamber, but is instead a seperate piece that is sealed to the front of the chamber with silicone. The larger tube insertion point is designed to work with 16 mm tubing for easier water transfer. The channel is much wider, and I made this change in the hopes that this chamber would be easier to flood with water. A much wider chamber theoretically meant it would be much harder for air to get caught in the different pockets. I hesitated to include an outlet for initial priming because I was still weary of avoiding leaks.

4 Fabrication

Manufacturing these tails presented interesting challenges in terms of adhering multiple parts together with silicone and working with large, complex molds. For concision, I am only including the successful attempts at manufacturing these tails so that anyone may validate my experiments if they wish. All files referenced here are found in the CAD files linked in the *Resources* section.

Before describing each fabrication process in detail, I would like to share some general tips on working with silicone.

- Always check a molded piece for leaks after it finishes curing.
- While EcoFlex 00-30 needs 4 hours to fully cure, you can take advantage of the fact EcoFlex seems to mostly cure in the first two hours.
- Always make more silicone than you think you'll need. Adding extra silicone to molds is easily rectified - just cut off the excess once the piece is finished curing. However, not adding enough silicone means you might need to wait another curing cycle to finish your piece.

- When mixing large quantities of silicone (more than 20 mL), be careful to minimize the introduction of air bubbles.
- When pouring silicone, pour it in a thin stream from high above your mold to minimize bubbles in the final mold.

4.1 Materials And Equipment

Before getting started, ensure you have the following materials, or suitable alternatives. This regardless of which tail you plan on making.

- 3D printer
- 3D printing filament
- EcoFlex 00-30
- Disposable measuring cups
- Popsicle sticks
- Cardstock paper
- Rubber bands
- Duct tape
- Exacto knife
- Flush cutters
- Vegetable oil
- Two syringes

Ensure you have the following additional materials for manufacturing the first tail.

- 16 M2*30 screws
- 13 M2 nuts
- 2 yards 1/8" OD x 1/16" ID Tubing
- Handful of zipties
- Needle

Ensure you have the following additional materials for manufacturing the second tail.

- 1 meter 16mm OD x 12 MM ID Tubing
- Hot glue gun
- Hot glue sticks
- Small hacksaw
- Sand paper

4.2 Tail 1

3D print all required pieces. These will be found in *RoboFish/Iteration 0/Required Stls*. Ensure that all molds are printed with extra top, bottom, and wall layers so that each piece is leak proof. I recommend 5 lines for walls, and 5 layers for top and bottom layers.

These are the steps to making one of the chambers. Repeat these steps to make two chambers.

1. Ensure that *Mold 1* fits snuggly with both *Mold 2* and *Mold 3*. If the pieces don't fit together, use an exacto knife or flush cutters to shave some material off of *Mold 2* and *3* so that the pieces fit snugly. This is important for molding.
2. Lightly coat the molding surfaces of *Mold 1* and *Mold 2* with vegetable oil. This will make it easier to remove the mold later on.
3. Fit *Mold 1* and *Mold 2* together. This will be for molding the tail. Cut duct tape into thin strips (about half inch) and wrap the duct tape around the combined mold. Wrap rubber bands around the molds to help keep them fixed together. Figure 5 shows a good example of how the duct tape and rubber bands should be applied. Note that the image shown is for the second fish tail, so your molds will have a different shape.
4. Place the combined mold onto a surface that can get messy. I recommend laying down some kind of disposable paper.
5. Mix approximately 80 mL of silicone in a disposable cup with a popsicle stick. Pour the silicone into the mold through one of the slits in the top until the mold begins overflowing with silicone.
6. Wait 4 hours for the silicone to cure.
7. Remove the tape and rubber bands from the combined mold. Cut any excess silicone on the surface of the mold. Carefully pry the top mold off. Use a popsicle stick of flathead screwdriver to help pry off the top mold.
8. The molded piece will likely pop out of the bottom mold, but stick to the top mold. Once it pops out, carefully pop the piece off of the bottom mold. I recommend popping out one rib at a time. Be especially careful not to break any ribs near the channel.
9. Success! We will temporarily call this piece, *Piece 1*.
10. Lightly coat the concave surface of *Mold 3* with vegetable oil. Place the mold your work surface.
11. Mix approximately 40 mL of silicone. Pour the silicone into the concave part of *Mold 3*. Use a popsicle stick to sweep across the top surface of the silicone to make it mostly flat.
12. Fit *Piece 1* into *Mold 1*. Fit *Mold 1* over *Mold 3*. This will make *Piece 1* adhere to the new piece with minimal deformation.
13. If possible, place a heavy object over the combined mold to keep the molds in place.
14. Wait 4 hours for the silicone to cure.
15. Remove *Mold 1* from the top, and peel the new piece out of *Mold 3*. Be careful not to rupture the bottom layer.
16. *Half Tail Piece* is now complete. It should look similar to the one in Figure 6.

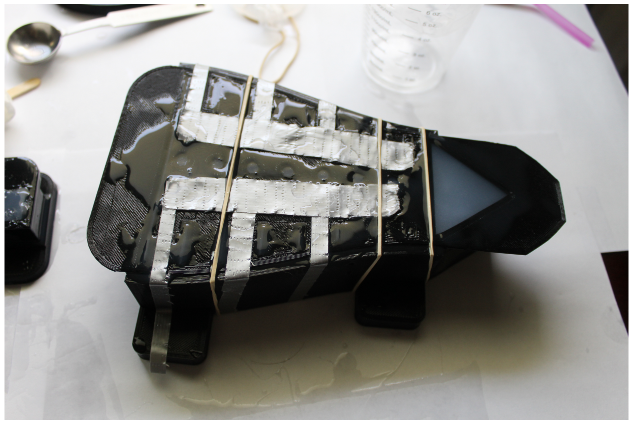

Figure 5: This is a good example of how a half tail mold should look when it is all set for curing. The molds shown are for Tail 2, but the principle applies to both tails.

Figure 6: This is a completed Half Tail Piece. Notice that there is a clean channel that connects all of the pockets.

These steps walk through how to mold a *Center Tail Piece* that goes between each *Half Tail Piece*.

1. Print out the *Tail Paper.pdf* file in *Required Stls*. Cut out two pieces of cardstock so that they are the same size as the outlined tail paper. Use whichever outline will fit nicely inside of *Mold 4*.
2. Coat the concave surface of *Mold 4* with vegetable oil.
3. Mix approximately 30 mL of silicone.
4. Pour a light layer of silicone into the mold.
5. Place the cardstock pieces into the mold.
6. Finish pouring the silicone into the mold.
7. Use a popsicle stick to flatten the silicone.
8. Wait 4 hours for the silicone to cure.
9. Peel the piece out of the mold.
10. *Center Tail Piece* is now complete.

These steps wrap up how to create the entire EcoFlex tail now that we've made two *Half Tail Pieces* and one *Center Tail Piece*.

1. Place *Mold 1* on your work surface.
2. Place one *Half Tail Piece* into the mold.
3. Mix approximately 20 mL of silicone.
4. Lightly coat the surface of the piece with about half the silicone.
5. Place the *Center Tail Piece* over the first piece.
6. Lightly coat the surface of the center piece with the other half of the silicone.
7. Place the second *Half Tail Piece* over the center piece.
8. Place a popsicle stick where the fin will go to keep silicone from flowing into that area.
9. Wait 4 hours for the silicone to cure.
10. After removing the tail from the mold, use flush cutters or a knife to remove excess silicone.
11. *Soft Tail* is now complete.

These steps walk through how to complete the fish assembly now that the *Soft Tail* is finished.

1. Push a needle through the two tube insertion points on the *Soft Tail*.
2. Cut the tubing into two equal lengths. Use the flush cutters to cut one side of each tube at a slant. Insert each tube into the soft tail using the side with the slanted cut.
3. Tie a ziptie around each tube insertion point. Tie them snugly, but not tightly. If you over-tighten, you risk pulling the insertion point off of the soft tail.
4. Test fitting the flange of the *Soft Tail* onto the head. If the flange does not, use a knife or flush cutters to cut off excess silicone until the entire flange fits into the head.
5. Add screws and nuts along the flange to secure the head pieces to the *Soft Tail*. Don't worry if a screw doesn't fit all the way through the flange. Just don't add a nut to it.
6. Route the tubing out of the large hole in the head pieces.
7. Add a screw and nut to the hole near the tip of the head.
8. Add 3 screws and nuts in a triangle formation on the tail so that the outermost mounting holes are filled.
9. Insert each open tube end into a syringe. Secure the attachment by wrapping it with duct tape, and tying the connection with a ziptie.
10. The first tail assembly is now complete. It should look similar to the assembly shown in Figure 7.

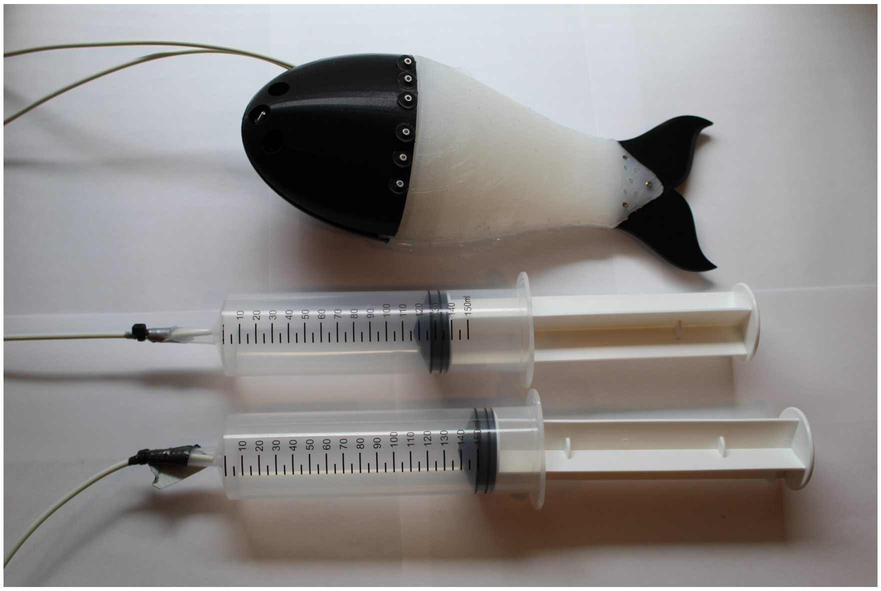

Figure 7: This is the completed assembly for the first tail.

4.3 Tail 2

3D print all required pieces. These will be found in *RoboFish/Iteration 1/Required Stls*. Ensure that all molds are printed with extra top, bottom, and wall layers so that each piece is leak proof. I recommend 5 lines for walls, and 5 layers for top and bottom layers.

These steps walk through how to manufacture the *Flange* of the tail.

1. Coat the inner surface of *Mold 1a* and the extruded surface of *Mold 2a* with vegetable oil.
2. Place *Mold 1a* onto your workspace with the open side facing up. Place the *Plastic Insert* inside the mold so that the extruded corners are facing up. Fit the extruded side of *Mold 2a* over that. Wrap a half inch section of duct tape around the lip where the two pieces connect. It should look similar to Figure 8.
3. Mix approximately 35 mL of silicone.
4. Pour the silicone into one of the holes in the top mold.
5. Wait 4 hours for the silicone to cure.
6. Remove the tape and the top mold from the mold assembly.
7. Use flush cutters to remove the excess cylinders protruding out of the piece.
8. Leave the finished *Flange Outer Piece* inside *Mold 1a*.
9. Place *Mold 2a* on your workspace, open side facing up. Coat the inner surface of *Mold 2a* and one side of *Mold 2b* with vegetable oil. Place the coated surface of *Mold 2b* over *Mold 2a*. Wrap rubber bands length-wise and width-wise around the combined mold. It should look similar to the one in Figure 9.
10. Mix approximately 25 mL of silicone.
11. Pour the silicone into one of the holes in the top mold.
12. Wait 4 hours for the silicone to cure.
13. Remove the tape and the top mold. Use flush cutters to cut off the excess cylinders.
14. Remove the finished *Flange Inner Piece* from the mold.

15. Mix approximately 10 mL of silicone.
16. Lightly coat the surface of *Flange Outer Piece* with silicone. Place the flat surface of *Flange Inner Piece* on top so that it is approximately centered.
17. Let pieces cure together for 4 hours.
18. The *Flange* is now complete. Let it sit in *Mold 1a*.

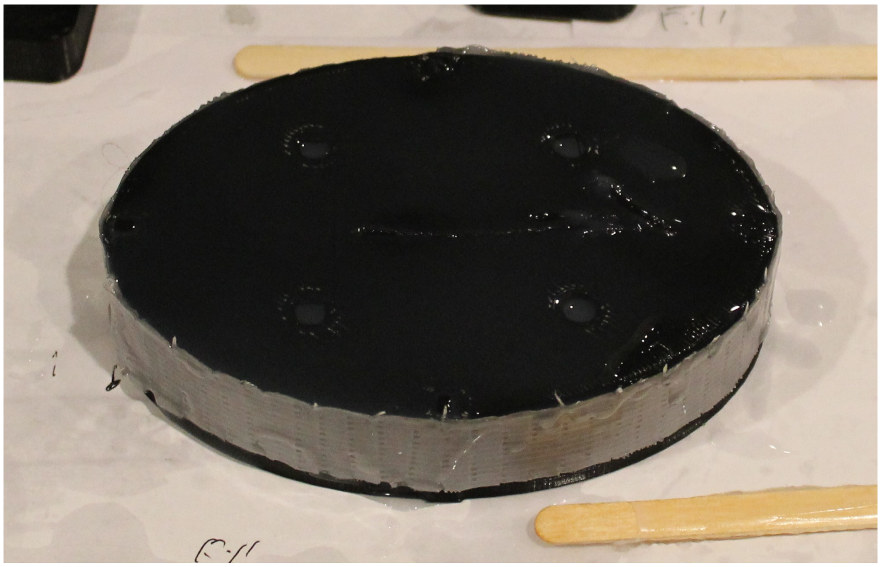

Figure 8: This is what the combined mold for the outer flange should look like once silicone is poured in.

Figure 9: This is what the combined mold for the inner flange should look like once silicone is poured in.

These steps walk through how to make a *Half Tail*, a chamber that holds fluid during actuation. Repeat these steps to make the second chamber.

1. Ensure that *Mold 3a* fits snugly into both *Mold 3b* and *Mold 3c*. If it doesn't, use a knife or flush cutters to shave outer layers of *3b* and *3c* until the molds fit nicely together.
2. Coat the inner surface of *Mold 3a* with vegetable oil, and coat the extruded surface of *Mold 3b* with vegetable oil.
3. Place *Mold 3a* over your workspace, open side facing up. Fix *Mold 3b* over it so that the extruded side is facing down.
4. Wrap quarter inch pieces of duct tape around the molds to keep them together. Wrap rubber bands around the molds as well. Refer to Figure 5 for an example of what this should look like.
5. Mix approximately 70 mL of silicone.
6. Pour the silicone in through the hole where the fin will attach. Be careful to minimize bubbles as you pour, and be patient in letting the silicone travel throughout the mold. This may take some time, but it helps reduce bubbles in the final piece.
7. Wait 4 hours for the silicone to cure.
8. Remove the tape and rubber bands. Cut excess silicone on the surface. Pry the top mold off. You may find wedging a popsicle stick or flathead screwdriver between the two molds helpful.
9. The top mold will likely pop off with the piece stuck to it. Pop the piece out of the top mold after that. The piece should look similar to the one depicted in Figure 10.
10. Cut the cylinders off of the tail at their base with flush cutters.
11. The *Outer Tail Half* is now complete. Place the piece back into *Mold 3a*. Add a piece of duct tape over the tube insertion point to help fix the mold to the piece.
12. Place *Mold 3c* on your workspace with the concave side facing up. Coat in the inner surface with vegetable oil.
13. Mix approximately 20 mL of silicone.
14. Pour the silicone into the mold.
15. Fix *Mold 3a* with the *Outer Tail Half* inside of it to the top of *Mold 3c*. This will make it so that when the silicone cures, the *Outer Tail Half* will fix itself to the fresh silicone. Place a heavy object over the combined mold to keep it from slipping.
16. Add extra silicone around the edges to ensure a complete connection.
17. Wait 4 hours for silicone to cure.
18. Remove the top mold first. Then, carefully peel the finished *Tail Half* off of the bottom mold.
19. The *Tail Half* is now complete. It should look similar to the one in Figure 11

Figure 10: This is a mostly finished Outer Tail Half.

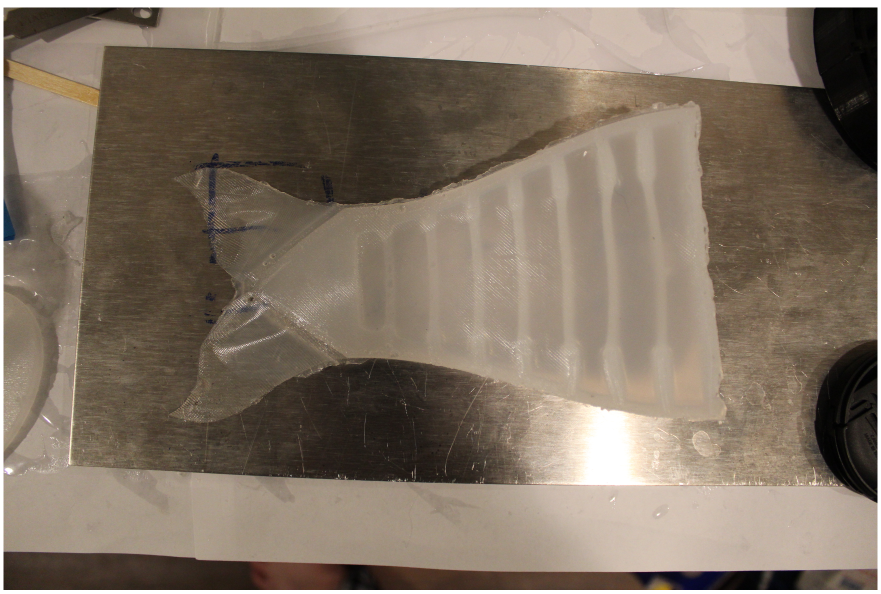

Figure 11: This is a finished Tail Half.

These steps walk through how to manufacture the complete tail.

1. Place one of the *Tail Half* pieces inside *Mold 3a*.
2. Place some object under the fin to hold the fin up to approximately the same height as *Mold 3a*.
3. Print out *Tail Paper.PDF* and cut one piece of cardstock paper to the shape of the bolded outline.
4. Mix approximately 20 mL of silicone.
5. Lightly and carefully apply a thin layer of silicone to the surface of the *Tail Half*.

6. Lightly place the cardstock paper so that the rounded edges on the flange-facing side line up with the rounded channel near the front of the tail.
7. Lightly and carefully apply another thin layer of silicone over the surface of the freshly added paper.
8. Place the other *Tail Half* so that it is lined up with the first one. The piece layout should look similar to Figure 12.
9. Wait 4 hours for the silicone to cure.
10. Remove the finished *Tail Chambers Piece* out of the mold.
11. Mix approximately 20 mL of silicone.
12. Place down *Mold 1a* with the *Flange* still inside it.
13. Coat the surface with silicone.
14. Place the *Tail Chambers Piece* over the *Flange* so that the paper is inserted into the opening in the *Flange*. Cut excess silicone off of the paper if necessary.
15. Balance the *Tail Chambers Piece* over the *Flange* so that it stays in place. Prop the entire tail against something if necessary.
16. Wait 4 hours for the silicone to cure.
17. Remove the completed tail from the mold. Wedging a screwdriver or popsicle stick into the mold to pry out the tail may help with this endeavour.
18. The *Soft Tail* is now complete. It should look similar to Figure 13.

Figure 12: This shows what the setup looks like for the last curing step for the Soft Tail.

Figure 13: This is what the completed Soft Tail should look like.

These steps walk through the process of completing the second tail assembly so that it can be tested.

1. Cut the tubing in half using the hacksaw. Smooth the edges with sand paper.
2. Insert one end of each tube into the tube insertion point in the *Soft Tail*.
3. Mix approximately 30 mL of silicone in a plastic cup. Do the same in another cup.
4. Wait 4 hours for the silicone to cure.
5. Remove the silicone from the cups. Poke a hole in the center of each cylinder of silicone.
6. Insert each syringe into one piece of silicone.
7. Cut the silicone so that the syringe can fit with the silicone attached into one end of the tubing.
8. Push the syringe into the tubing, and add hot glue around the rim to help it stay connected.
9. Add duct tape connecting the tubing to the syringe to keep the syringe connected.
10. Do this with both syringes. The goal is to make the connection as watertight as possible.
11. The second tail assembly is now complete. Without the tubing, it should look similar to Figure 14.

Figure 14: This is what the completed tail assembly should look like for the second tail without the tubing.

5 Testing

5.1 Tail 1

5.1.1 Half Tail Pneumatic Inflation test

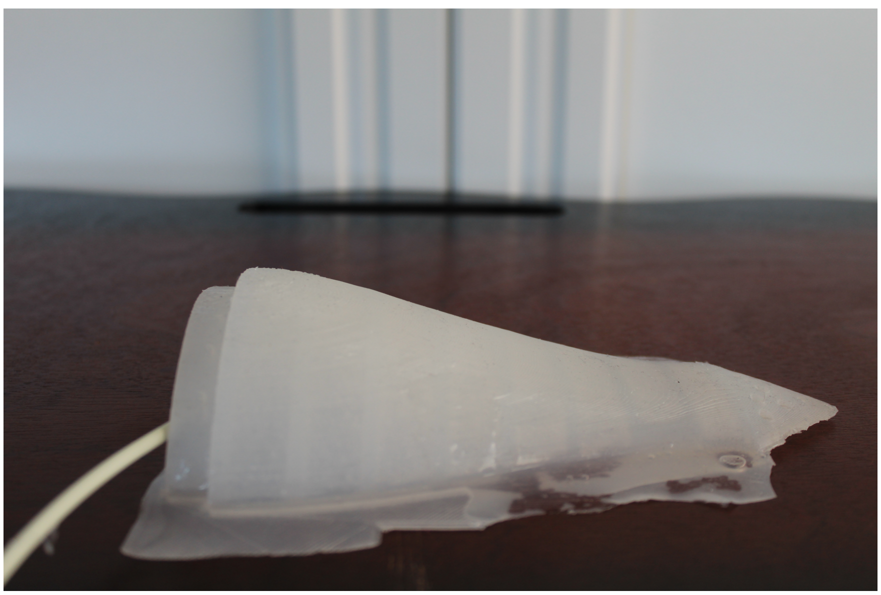

Figure 15: This shows the setup for the first test of whether or not the chamber would inflate properly.

The first thing I wanted to test was whether the chamber I designed inflated properly. Figure 15 shows what the setup for this test looked like, and this link will take you to the full video of the test. The chamber inflated with air when I squeezed the syringe, and air was effectively divided amongst the different pockets. One interesting thing to note is that the chamber was thinner along the bottom of the half-tail. That made it so that pressure more easily pushed the bottom outwards, while not affecting the top as much. This was desired as the bottom piece was where I wanted pressure to go so that it would push against the rigid component in the full tail to cause the tail to curve. I also noticed that pumping air in and out of the chamber manually did not meet much resistance.

5.1.2 Full Tail Pneumatic Inflation Test

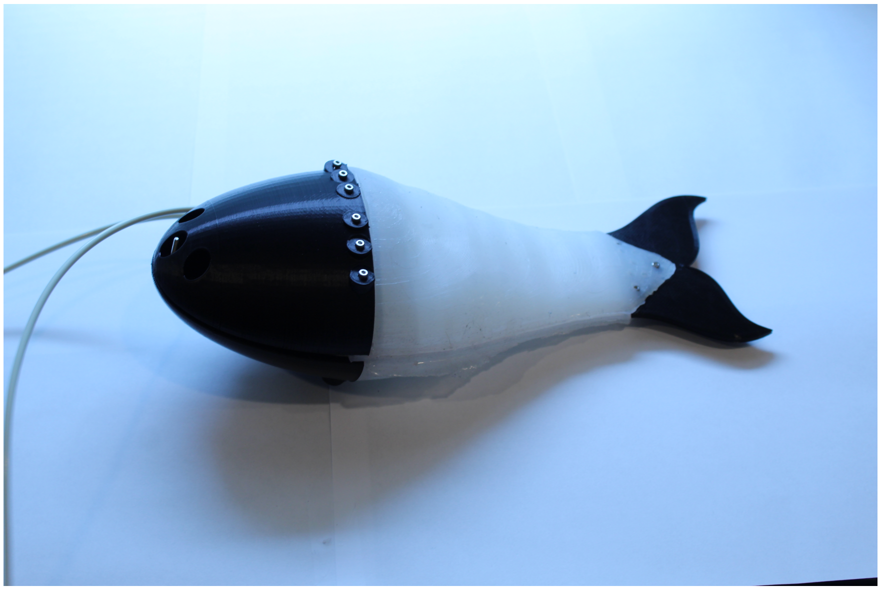

Figure 16: This shows the setup for the test to see if the tail would curve when one chamber was pressurized while the other was depressurized.

Once I knew both chambers would properly inflate with air, it was time to test whether I could create curvature in the full tail. Figure 16 shows the setup for this test, and this link will take you to the full video of the test. The full tail swayed back and forth as air was transferred between the two chambers. Pressurizing one chamber while depressurizing the other definitely created a curve along the middle of the tail. However, the pressurized chamber also seemed to inflate. This meant that pressure that might have been able to go inwards towards bending the fish tail was instead pushing the outside of the tail further outwards. This wasn't the case with SoFi. This seems to be due to the fact that my fish has a relatively thin outer skin, with wide spaces between its ribs. The SoFi tail seems to have a slightly thicker skin, and much narrower spaces between ribs. The rigid fin at the back of the fish seems to follow the curvature of the tail and extend that curvature all the way to the fin. This ensured that although there was no pressure to cause a curve in the end of the tail, it still curved with the rest of the tail. While this test proved that this tail worked, it also showed that a significant volume of air at atmospheric pressure was required to inflate a chamber. This made it unlikely that it would be possible to achieve significant motion through pumping air between these two chambers without any external reserve of air.

5.1.3 Full Tail Pneumatic Water Test

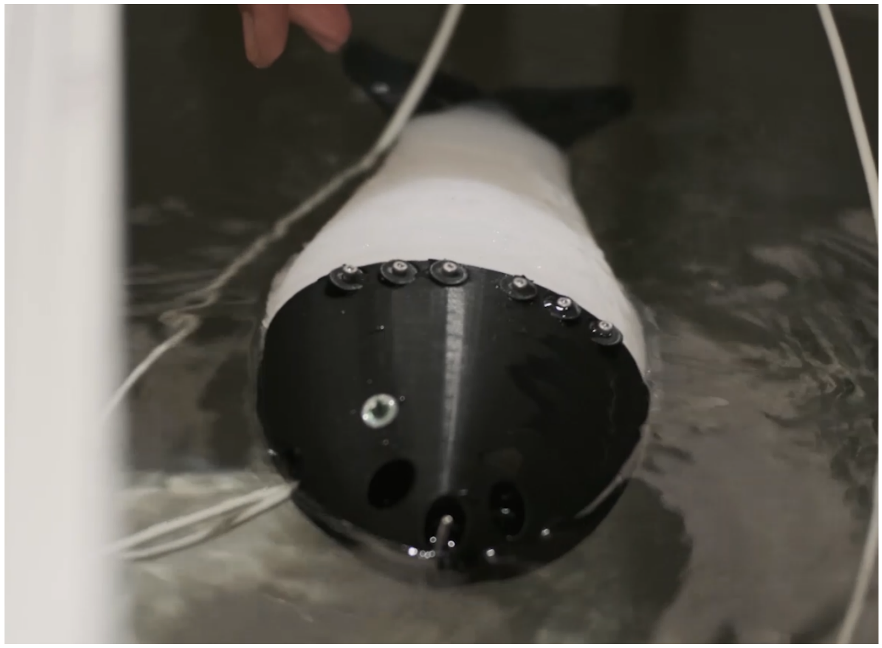

Figure 17: The first tail assembly floats in the water when its chambers are filled with air.

I placed the tail into the water to see how it would interact with the water. Figure 17 shows what the tail did when placed in water. Because its chambers were full of air, the fish simply floated on the surface of the water. I realized that to make the fish neutrally buoyant, I would need to add weight to the fish in the head so that it would sink instead of float. However, that would pose the initial challenge of appropriately distributing weight across the fish so that it wouldn't sit lopsided in the water, or roll uncontrollably. The idea of trying to make the fish neutrally buoyant was further challenged by the fact that air is a compressible fluid, meaning that it would be difficult to predict how the volume of the chambers would change as air was added into them. While not impossible to model, the effort did not seem worth the return on investment as opposed to just switching to hydraulic actuation. Since water is in-compressible, any volume of water added to a chamber would increase that chamber's volume by the volume of the water added. That would keep the density of the fish easy to predict. In the ideal case where water would be pumped between the two chambers, the density of the fish would remain constant.

5.1.4 Flooding Chambers

In order to perform any type of hydraulic tests on this tail, I would need to first force all of the air out of the chambers and replace it with water. This posed a significant challenge for various reasons. There was only one entry/exit point on the tail where water would have to go in and air would have to come out. Additionally, the channel connecting the pockets together was quite small at a few millimeters squared. These factors made it easy for air to get trapped in the pockets throughout the tail. The most effective method I found for removing air from the chamber was holding the tail completely underwater, with the entry/exit point facing upwards, and squeezing as much air out as I could. Once the chambers were as empty as I could make them, I inserted the tubing and pumped water back into the chambers. I managed to remove most of the air from the chambers, but could not remove all of it.

5.1.5 Full Tail Hydraulic Actuation Test

Figure 18: The first tail assembly successfully moved its tail back and forth underwater, though it did so incredibly slowly.

I placed the now hydraulic fish tail underwater, and tested it to see if it would be feasibly possible to actuate the tail hydraulically underwater. Figure 19 shows what this test setup looked like, this link will take you to the full video of the test. The video is sped up 5x. The tail can certainly be actuated hydraulically, but it takes much longer to pressurize and depressurize the chambers. This is largely due to the fact that it was extremely challenging to pressurize and depressurize the chambers manually. The thin tubing and thin channel likely added a lot of resistance to moving water in and out of the chambers. The hard fin seems to extend the curvature of the tail in water, as the fin still follows the curve of the tail even though there is no pressure being applied at the end of the tail. The tail also seems to have this problem where the pressure is still noticeably pushing the chambers outwards, suggesting that a thicker outer skin would result in more of this pressure contributing to the curvature of the tail.

5.2 Tail 2

5.2.1 Flooding Chambers

The second tail was much easier to flood with water, but still presented challenges in removing all of the air from the chambers. While a similar technique from the first tail worked to get out most of the air, some air still remained in some of the pockets of the tail. However, it was much faster to squeeze air out of the second tail compared to the first tail, likely due to its wider channel and larger entry/exit point.

5.3 Hydraulic Actuation Test

Figure 19: The second tail successfully moves back and forth underwater. However, the second tail does not curve nearly as much as the first tail.

I submerged the entire tail, and held it underwater so that it wouldn't drift away. I wanted to test whether this tail would be possible to actuate hydraulically underwater. Figure 19 shows the setup for this test, and this link will take you to the full video of the test. While the chambers were much easier to pressurize and depressurize, the maximum curvature of the tail significantly declined. The chambers were likely easier to pressurize in large part due to the wider tubing. I tested pushing water through the thin tubing and the wider tubing when each tube was disconnected from the fish, and noticed it was much easier to push water through the wider tubing. The wider channels may also have contributed to this.

When one chamber was fully pressurized and the other was fully depressurized, there was only a slightly noticeable curve in the tail. The second tail also had a more pronounced problem with pressure going towards inflating the tail outwards instead of creating curvature in the tail. These effects were both likely due to the wider channels and a less rigid middle piece. With wider channels, the chambers act less like Pnuenets and more like balloons. The ribs help create a curve in the tail by pulling the outer skin towards the center of the tail. Removing material from these ribs likely caused a less pronounced curve. The rigid middle piece also helped to create a curve in the tail by causing a pressure difference between the outer skin and the middle that caused the middle piece to compress and the outer skin to expand. By using only one piece of cardstock, and making a thinner middle out of silicone, I likely made the middle piece far less effective at causing the tail to curve.

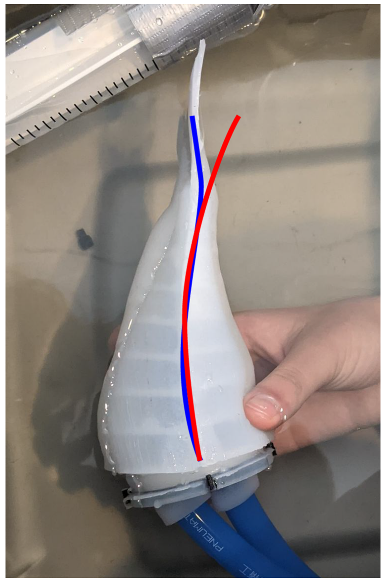

Figure 20: The blue curve here represents the actual curvature of the tail while the red curve represents the desired curvature of the tail. The discrepancy is likely due to the lack of a rigid fin.

Another important observation is shown in Figure 20, which shows that the curve of the fish tail is not a first order curve. Instead of bending completely in one direction, the tail mostly bends in one direction until we move closer to the fin. The fin does not extend the curve of the main body of the tail to the back of the tail. Instead, it seems to resist the curve and stay somewhat perpendicular to the front surface of the tail. This is likely due to the fact that the second tail's center piece is far less rigid than the first tail. Not only does this tail lack a completely rigid fin. This tail also uses a thinner layer of silicone for its center piece and uses only one piece of cardstock instead of two for rigidity.

6 Reflection

6.1 Overall Reflection

I feel like I definitely accomplished a lot on this project in terms of creating all of these different molds and tinkering with different fish designs, but overall, the project lacked the simplicity that makes experiments useful. For the first iteration of SoFi-mini, I did not spend much time going in depth with prior research before jumping into my design. I learned the basic idea, looked through some diagrams, and hit the ground running on my design. I traded time I could have spent informing my design for time I actually spent delving into my design with less prior information. At that point, I think I was still headed in the right direction. I could gain a far better intuition for how the soft tail would work if I had one in hand to tinker with. However, once I completed my first fish, I should have spent more time analyzing its behaviour and planning what I wanted to learn from my next tail before diving into making another one. Instead of using the first fish as a tool for building a stronger intuition of how the soft tail should work, I treated it as a quick stop before making a more complex iteration. Had I stopped to analyze the first tail further, alongside a deeper dive into the literature, I could have made a more effective plan for what I wanted to learn from building my second tail. This certainly would have guided my direction for the second tail away from the rabbit holes I went down and towards simpler changes that would maximize my investment into making another tail.

6.2 Learning Goals Reflection

I definitely met my learning goals for this project. I was most interested in learning how to work effectively with EcoFlex, and that was what I spent most of my time doing for this project. The first custom mold I made for the fish tail actually resulted in a mess of silicone, and that was only for one part. The second tail I made was actually a combination of 6 parts made of EcoFlex, and 1 part made of plastic. In the time in between, I learned how to design molds to reduce air bubbles, to use mold release, how to reliably combine EcoFlex parts together, and generally how to design molds and work with EcoFlex.

6.3 Next Steps

For the next steps on this project, I would move back to the first fish tail, and make simple improvements on that fish tail, one at a time, to methodically test how to improve the fish tail. I would also dive deeper into what made SoFi's tail successful, and apply those findings to my fish tail. Some of the factors I would vary include the width of the channel, the width of the pockets, the width of the ribs, and the number of ribs in a tail. I would also build some kind of testing rig for holding the fish tails underwater to make testing easier, and more consistent. Additionally, I would quantify the curvature by fitting discrete points on the tail to a polynomial equation rather than just qualitatively analyzing the performance of the fish tails.

6.4 Resources

Link to CAD Files: https://grabcad.com/library/robo-fish-1

Link to Video Demos: https://drive.google.com/drive/folders/18p3RASjQtDWxtTSzaUh-Agym5vpvWauf?usp=sharing

7 Works Cited

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