Blue Guppies Project: A Miniature Fish Robot

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Princeton University

I hereby declare that this Independent Work report

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Abstract

Understanding hydrodynamic interactions of school of fish is a pivotal step towards studying the field of emergent collective behaviors. Researchers have mostly been studying movements of objects in air with the hope of further understanding and developing of fields such as algorithms and artificial intelligence. However, it is important to note that small fish such as tetras, sardines, and guppies demonstrate complex coordinated movements as a group. These fish in school match the vortex phase in the fluid environment, but it is unclear if this phenomenon requires sensory feedback. As part of the Princeton Self Organizing Systems Research Group, this project, Blue Guppies Project, aims at designing a miniature fish robot, about 10cm long, that can assist researchers in studying and understanding the field of emergent collective behaviors in schools of fish. This independent work details a brief analysis of the field of emergent collective behaviors, other low-cost robots designed by researchers in this field, design of the Blue Guppies fish robot, and future directions for this project.

ACKNOWLEDGMENTS

I want to thank Professor Radhika Nagpal for first taking me into her research group this spring semester. Her phenomenal outreach and mentorship endeavors with the NSBE (National Society of Black Engineers) group really made it possible for me to pursue some of my interests in robotics while immensely learning from her. I am thankful for her unwavering support and guidance throughout this research, and for introducing me to the field of swarm robotics through her extensive research experience and insights. Furthermore, I have had the privilege of attending the weekly Wednesday lab meetings, where I have been able to listen to incredible projects from other members of the lab. Her mentorship extends beyond research, and I am indebted to her for all the knowledge and wisdom she has imparted to me.

I want to thank Dr. Hungtang Ko as I feel so grateful for working with such an exceptional mentor and researcher. Under his guidance, I acquired valuable skills, such as research enthusiasm and confidence, through his exemplary problem-solving techniques and work ethic. Dr. Ko's guidance also helped me to persevere through moments of uncertainty. His mentorship has been instrumental in my personal and professional growth, and I credit my current success to his guidance. Thank you for providing feedback on this report and the overall project. Working with him has been a transformative experience, and I consider myself fortunate to have had the opportunity to learn from him.

I would like to express my gratitude to Baffour Osei for his guidance and generous provision of equipment at the Robotics Lab, which has greatly enhanced my learning experience. The opportunity to use the 3D printers in the lab has been particularly beneficial, and I have also greatly appreciated his kindness and humility. I extend my sincere thanks to the other members of the lab group for their unwavering support and willingness to assist with any inquiries.

Thank you to my second reader, Dr. Hossein Valavi, for his continuous and everlasting love, support, and guidance. His invaluable contributions have been a true blessing.

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1. BACKGROUND

1.1. Emergent Collective Behaviors

Emergent collective behaviors are patterns of behavior that emerge among groups of individuals interacting spontaneously without any central control. These behaviors can be observed among various groups such as ants and bees, flocks of birds, schools of fish, or even in decision-making among a human-group. The purpose of emergent collective behavior is such that a group can achieve a more complex task that could have been difficult for a single individual.

For example, a colony of bees works in a collective manner, where all the bee workers work together towards building a bee comb, handle incoming nectar, guard the bee comb as well as take care of the queen. Another instance of this phenomenon can be observed in honeybees, who tend to clump together to survive a blowing wind [1].

Figure 1: Honeybees clumping together surviving a blowing wind.

Therefore, it comes with no surprise that emergent collective behavior is an interdisciplinary field that draws inspiration from many fields including biology and computer science. According to researchers in Banff International Research Station for Mathematical Innovation and Discovery, emergent collective behaviors are often similar among different species. As suggested by the researchers, this commonality hints at collective behaviors having some aspect of universality; although there's currently no underlying theoretical description of this universality. Therefore, most of the research in emergent collective behaviors is conducted either through experimental observations or on computer simulations. Shown below is another example of collective behaviors in birds:

Figure 2: A flock of birds in Costa Brava, Northeastern Spain, gathering in a shape-shifting cloud, known as a murmuration

Thus, the study of Emergent Collective behaviors has diverse applications in the real world, ranging from swarm robotics, construction sites and traffic management to social network analysis and disaster response planning. By understanding how collective behaviors arise, researchers and engineers can develop more resilient, adaptable, and efficient systems that can potentially save lives and aid in improving workflow.

Researchers in other academic fields such as Sociology have also analyzed forms of collective behaviors among humans. Flash mobs are an excellent example of how emergent collective behaviors can cause change [2]. Let's not forget how leaders from Bolivia to Sudan were overthrown simply by the power of protests, where collective action by groups of people was deployed [3].

1.2. The Kilobot

One of the challenges that many researchers faced towards studying the field of emergent collective behavior was the construction of a massive array of robots at low-cost while still able to perform some common tasks [4]. Inspired to solve these challenges, Prof Radhika Nagpal and Prof Michael Rubenstein began the development of the Kilobot in November 2010 with the support of the Wyss Institute for Biologically Inspired Engineering and the National Science Foundation [4]. The primary aim of the Kilobot's design was to ensure affordability while providing sufficient functionality to perform various collective tasks [4]. One of their objectives was to enable the Kilobot capable of executing the SDASH program [4].

The SDASH (scalable, distributed self-assembly and self-healing) is an algorithm that was developed to self-assemble and self-heal a collective shape [4], [5]. To execute SDASH, a robot must possess the abilities to move forward, rotate, communicate with nearby units, and measure the distance between them [4], [5]. Moreover, it should have sufficient memory to run the algorithm [4], [5]. To expand the potential applications of the Kilobot, developers incorporated additional features such as the ability to measure ambient light levels and support scalable operations [4], [5].

1.2.1. Design

The Kilobot was designed using very low-cost materials totaling about $14 [5]. The major components used are as follows:

- Rechargeable lithium-ion batteries that can sustain the Kilobot for 3-12 hours, depending on their level of activity [5].
- Three-color LED that displays information to the user [5].
- Two vibrators for movement [5]. Because the Kilobot stands on 3 legs, the vibrators enable the Kilobot to turn at a rate of about 45° per second when either vibrator is activated and move forward at a speed of roughly 1 cm/s when both are activated [5]. Vibrators were used instead of wheels to minimize cost [5]
- Infrared LED Transmitter and Photodiode receiver [5]. Each Kilobot had both parts underneath their PCB boards to aid in communication [5]. One robot sends light towards the surface, which reflects up to the receiver of a nearby robot, which then executes a command based on the program [5].

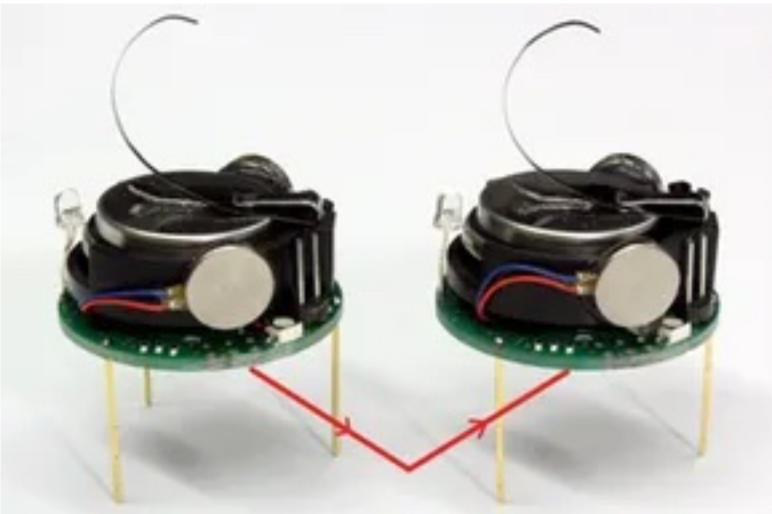


Figure 3: Two Kilobots communicating with each other

1.2.2. Applications

The Kilobot was a major step towards the cost-effective studying of emergent collective behaviors among a collection of groups [4]. The Kilobot was designed to imitate the behavior of insect swarms, where each Kilobot can work together to achieve collective transport of a large object, and form and repair different shapes using the SDASH algorithm [4]. The Kilobots are also able to adjust their size, depending on the shape formed [4].

1.3. Smarticles

A few years later researchers from Georgia Tech in collaboration with researchers from Northwestern University sought of building a different type of robot that can demonstrate a different locomotion technique [6]. This time, researchers inspired by the Purcell's three-link swimmer model, sought to make a robot from smaller robots-known as smart active particles(Smarticles) [7]. The 3D-printed Smarticles flap their two-arms and when a couple of them are encircled in a circle they begin to nudge each other and create movement [6].

1.3.1. Design

The Smarticles was designed using the following components:

- HD-1440A servomotors for controlling the arms of the Smarticles to a precision of $<1°$ and with an accuracy of $\pm 6°$ [7]
- 3.7-V, 150-mAh, 30-C LiPo battery for powering the Smarticle [7]
- Photosensors such that when a strong beam of light is casted at a proper angle, you can highlight the Smarticle you want to be inactive [7].
- Ring to enclose the Smarticles [7].

1.3.2. Applications

The Smarticles was a significant milestone in comprehending intricate locomotion patterns [6]. Despite the unpredictable flapping movements of individual Smarticles, the entire robot demonstrated predictable motion [6]. Additionally, constructing the Smarticle from smaller robots using just the fundamental principles of Mechanics and Kinematics instead of advanced computations and sensing opened new possibilities for traditional robot manufacturing [6].

1.4. Emergent Collective Behaviors in fish schools

Fish schools are groups of fish that move together in a coordinated way without central control. This behavior happens because each fish interacts with neighboring fish and their environment. Each fish follows simple rules, such as keeping a certain distance from others and moving in the same direction. However, these simple rules in individual fish result in complex behaviors such as changing direction or speed to swim more efficiently or to confuse predators. As such, this complex coordinated movements are of interest to scientists because through computer simulations scientists can understand how collective behavior and feedback mechanism arises and help create better underwater vehicles and improve biomimetic robotics.

Figure 4. Collective movements of a fish school

For example, a study by the National Library of Medicine, suggested that fish swimming in schools have reduced costs of swimming thus saving more energy than fish swimming individually at the same speed. Swimming in the wake of another fish was previously known to save energy, but this study also found that even fish swimming ahead of another fish gained an energetic advantage compared to swimming alone [8]. These findings have significant implications in different industries. This great landmark discoveries outline the importance of continued research in such fields, such as our project.

2. Design of the Blue Guppy robot

1.5. A Blue Guppy Fish

Small fish such as tetras, sardines and guppies demonstrate complex coordinated movements as a group. It is noteworthy that the designation of the project name was not based on the specific types of fish, but rather the size of the fish. Therefore, any school of small fish would have been applicable to the project's nomenclature. Furthermore, it is important to emphasize that the selection of the blue guppy fish robot design was not intended to directly reflect the characteristics of the actual blue guppy fish.

1.6. Components of a Blue Guppy Robot

Our key goal was to develop a miniature fish robot that resembles a blue guppy with a single-tail fin. The Blue Guppy Robot fish is about 10cm long, which is comparable to the actual Blue Guppy fish (~6.35cm long). The Blue Guppy miniature robot was 3D printed using PLA material because PLA is biodegradable and has minimal warping behavior.

1.6.1 Motor box

As the name suggests, the motor box was specifically designed to fit a high-torque motor. There were two major parameters in consideration when designing the motor box: height (to match corresponding motor) and a rectangular sledge inside it.

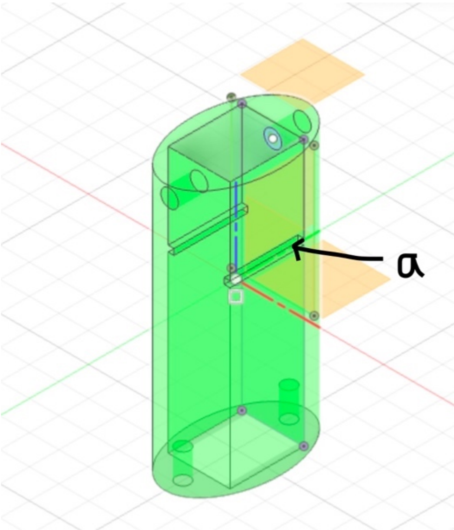


Figure 5: Schematics of the Motor box, **a** = rectangular sledge for allowing the motor to be placed from underneath thus preventing the motor from falling when held upside down

It is worth emphasizing that various versions of the design were created, so it was deemed necessary to present both designs to offer readers an analysis of what was done and why, as demonstrated below.

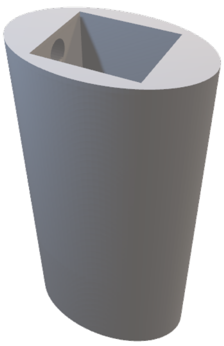


Figure 6: Current 3D model of motor box

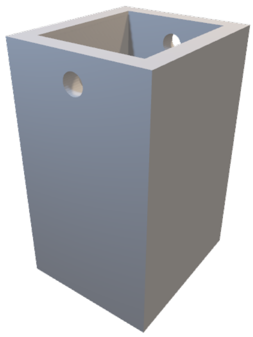


Figure 7: Previous 3D model of motor box

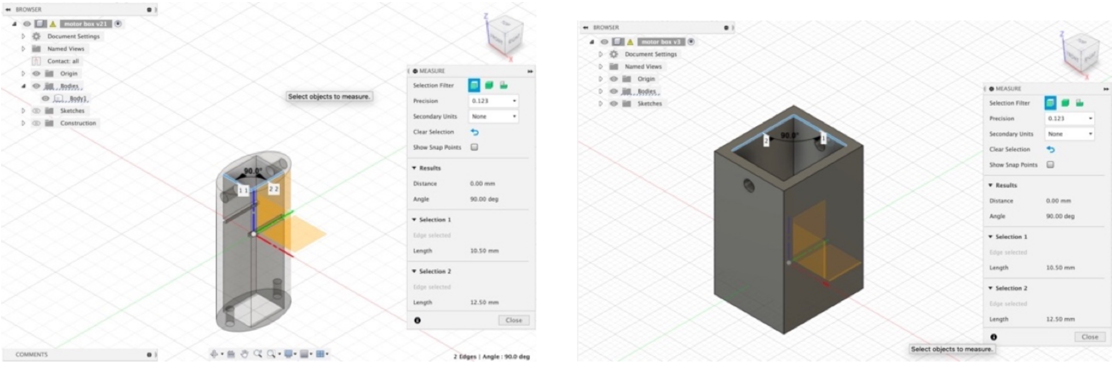


Figure 8: Both models have the same dimensions for the inner square proving this was not the area of interest for our change of designs

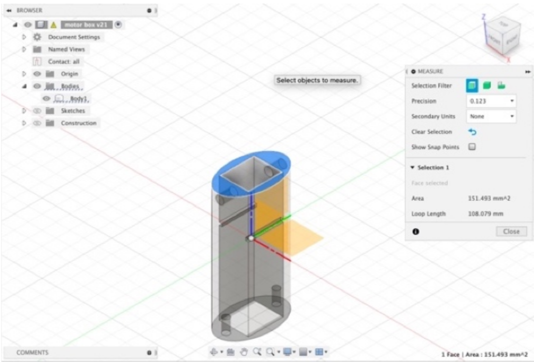


Figure 9: Current model with inner area of 151.493 mm^2

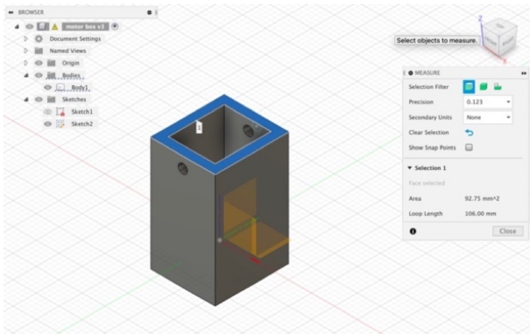


Figure 10: Previous model with inner area of 92.75 mm^2

Therefore, the area of interest was increasing the “area” of the inner spacing between the rectangular block and the outer surface. Increasing the “area” of interest came along with various benefits such as increased buoyancy of the Blue Guppy fish because the weight of the motor and the batteries brought about a huge increase in the overall weight of the motor box. The following calculations were used to determine this:

Figure 11: showing how the change in current design managed to increase the volume by 4418.522mm^3

- The actual motor used for the Blue Guppy miniature fish was the N20 High Torque Motor which weighs about 9g.
- With older version:
  - Density of the motor box + motor = $\frac{Mass}{Volume} = \frac{18.116+9g}{2307.754mm^3}$ = 0.0117g/mm^3
- With current version:
  - Density of the motor box + motor = $\frac{Mass}{Volume} = \frac{52.801+9g}{6726.276mm^3}$ = 0.00918g/ mm^3

Decrease in density = 21.47%

Thus, the change in design brought about a decrease in density of about 21.47% which is effective in compensating for the increase in mass from the N20 High Torque Motor.

Motors of the same size but different gear ratios were selected to vary performance. Motors with lower gear ratio were of particular importance to this project because of increased rotations and thus faster flapping of the tail fin of the Blue Guppy fish robot.

In terms of 3D printing, it was observed that the orientation of the layout of the motor box mattered. For instance, when the motor box was laid with the two pin holes on the printing surface of the Ultimaker, the holes were found to shrink after the print. Therefore, it was important that the motor box was laid with the holes facing up to avoid this. Otherwise, it was found that printing with the pin holes laid down could be salvaged by either choosing the brim or skirt options in the Ultimaker settings.

1.6.2. Flapper + Bent Shaft

1.6.2.1 Flapper

Another component that was used and critical for the Blue Guppy's movement is the flapper. The flapper was 3D printed with the extra fine profile setting in Ultimaker Cura to improve rigidity. This was primarily crucial because the movement of the flapper needed to withstand intense forces when immersed in water, as well as accommodate the elasticity of the molded skin. As a result, it was crucial that the flapper was firm and rigid and not easily breakable.

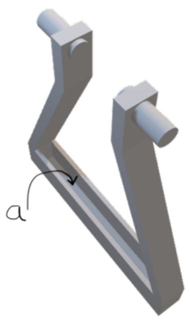


Figure 12. A 3D model of the flapper

a = rectangular spacing inside the flapper

Figure 13. A 3D printed flapper

3D printing the flapper came with various challenges. Because the bent shaft moves inside the flapper, as demonstrated in the next pages, the rectangular spacing inside it needed to be smooth. However, this wasn't always the case when 3D printing the flappers. Most prints came with rough abrasions, where there were still non-uniform/incomplete layers of

PLA inside it. This type of flappers would barely flap with normal 3–4-coin batteries. This is because the abrasions brought about increased friction between the shaft and the flapper.

Figure 14: Flapper with uniform spacing inside

Figure 15: Flapper with rough abrasions

There's wasn't as many iterations of the flapper as compared to the design of the motor box. Most iterations of the flapper were focused on increasing the flapper length to ensure that there was a much larger amplitude of oscillation of the flapper as possible. A much large amplitude would ensure that the fish can easily flap even with the molded skin woven around it especially because the skin proved to be a good waterproofing agent, but very resistant to the movements of the flapper.

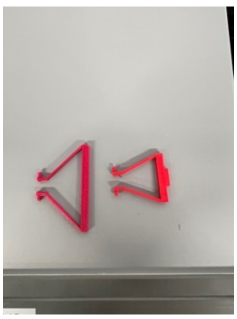


Figure 16: Different flapper lengths

1.6.2.2. Bent Shaft

The flapper and the shaft go together. The bent shaft was also 3D printed using the extra fine profile setting in Ultimaker Cura to improve rigidity. This time, the aim was to ensure that the shaft doesn't break as it moves across the uniform rectangular spacing of the flapper. This is described further in the driving mechanism of the Blue Guppy fish robot. Also as mentioned, different flapper lengths correspond to different designs of the bent shaft. This is particularly noted because the rotational angle at which the bent shaft can move across the flapper is of most significance to avoid beating the side faces of the flapper.

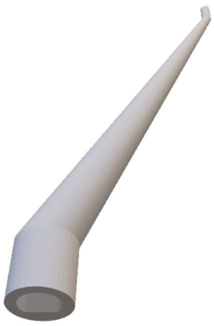


Figure 17: A 3D model of a bent shaft

Figure 18: 3D printed bent shaft

1.6.3. Battery Box + Cap

A battery box containing 2 conducting flaps was used to store 3-4 Lithium-Coin 3V batteries. The cap, as the name suggests, was used to close the battery box by both screwing and placing small rubber lobe inside it. The small rubber lobe was placed to ensure that no water was able to enter inside the battery box.

Figure 19: Rubber lobe inside the battery cap.

The battery box has a narrow path from the top to the bottom to insert a copper wire for + - battery connection as demonstrated below:

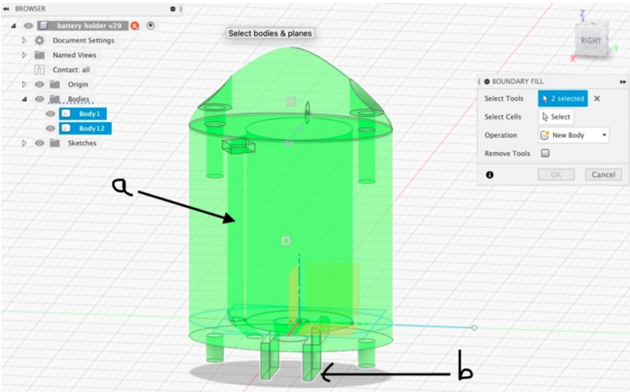


Figure 20: Showing the schematics of the battery box + cap.

a = narrow path for placing a thin copper wire to connect the +- battery connection

b = conducting flaps for the circuit completion

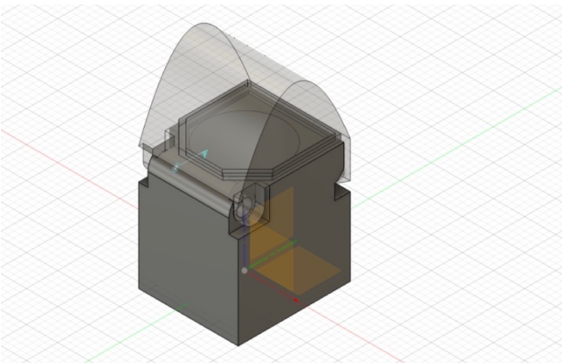


Figure 21: Previous version of battery box

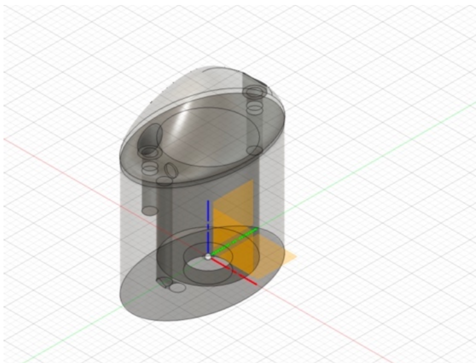
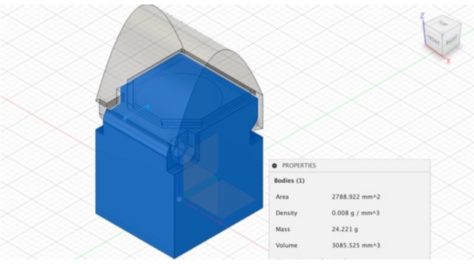


Figure 22: Current version of battery box

The change in design from Figure 21 to Figure 22 was made first to enable the battery box fit the motor box. Because as previously discussed, different changes were made to the motor box to increase the overall volume which decreased density of the overall fish, then the corresponding battery box had to also be changed. In addition, this structure also came with some additional advantages like those outlined in the motor box:



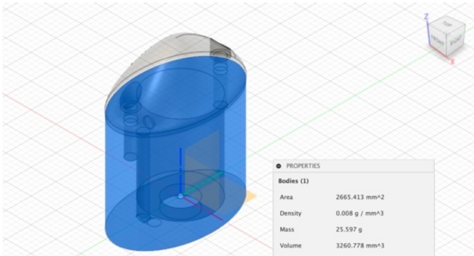


Figure 23: showing how the change in current design managed to increase the volume by 175.253mm^3

- 1 Lithium-Coin 3V battery = 3 ounces
- 1 ounce = 0.028kg
- With older version:
  - Density of the battery box + 3-coin batteries = $\frac{Mass}{Volume} = \frac{24.221+9(0.028*1000)g}{3085.525mm^3}$

    = 0.0895g/mm^3
- With current version:
  - Density of the battery box + 3-coin batteries = $\frac{Mass}{Volume} = \frac{25.597+9(0.028*1000)g}{3260.778mm^3}$

    = 0.0851g/ mm^3

Decrease in density = 4.88%

Thus, the change in design also brought about a decrease in density of about 4.88% which is effective in compensating for the increase in mass from the lithium-coin 3V batteries.

1.7. Driving Mechanism

The driving mechanism of the Blue Guppy was inspired by the research paper, "*Tuna robotics: A high-frequency experimental platform exploring the performance space of swimming fishes*". The Blue Guppy fish robot is powered by coin batteries located in its battery box. Using the standard 3-batteries in the battery box supplies 4.5V to the motor. The motor drives the bent shaft which in turn moves across the flapper. Because the shaft is bent and is restricted by its movement inside the flapper, the shaft's movement leads to an up-and-down movement of the flapper thereby closely mimicking flapping of fins in fish.

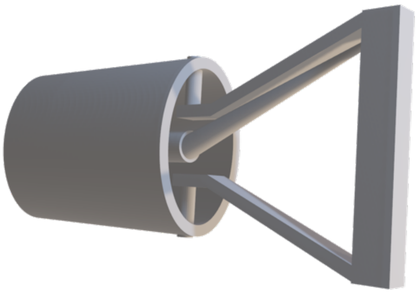


Figure 24: Motor box + Flapper + Shaft

1.8. Waterproofing

For waterproofing the fish, a silicone mold was made by using Smooth-On Eco-Flex Part A & B products, as well as a Smooth-On Mann Ease Agent. The Manufacturing of the skin involved the following procedures.

- 3D printing two cases and a tail mold for determining the physical dimensions of the skin. The mold is eventually poured into these cases and thus casted on the fish.

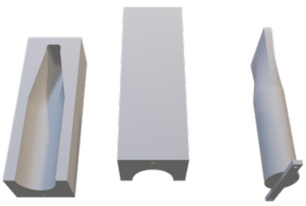


Figure 25: Two outer cases with a tail mold

- Spraying a release agent inside every component above to ensure that once the skin is fully solidified it can easily be removed.

- 1:1 Mixing of Smooth-On Eco-Flex Part A & B products and stirring them thoroughly. Half an ounce of each product was considered enough to make the silicone mold.
- Screwing the three components together and pouring the silicone mold inside the tiny spacing and leaving the setup inside a vacuum chamber for roughly 24 hours.

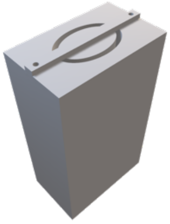


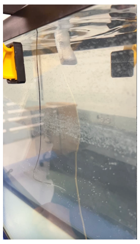
Figure 26: When tail mold and cases are combined screwed and screwed at the top.

Figure 27: Silicone(mold) skin

3. Underwater Tests

1.9. Underwater Test Setup

Various tests were performed under water to determine the ability of the fish to flap under water. Blue Guppy was able to successfully flap under water. However various tests such as casting a laser beam across the water currents showed moreover particles of water spreading outward other than downward, as the setup shown, which is important for propulsion of the fish. Therefore, more research on design methodology is to be done to improve the current version.



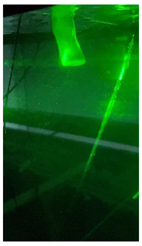


Figure 28: Underwater test setup

Figure 29: Underwater test with laser beam

1.10. Determining Density of Fish

For calculating density of fish, the traditional route was used by considering the Archimedes' principle. (Bolded data represents data used for the calculations)

- **Mass of full Fish(skin + motor + 3 batteries) = 42.2g**
- Mass of red cylinder = 54.7g
- **Mass of red box + water = 330.7g**
- **Mass of red box + water + fish = 372.8g**
- **weight of displaced water = 372.8g – 330.7g = 42.1g**
- Relative Density of fish = $\frac{Mass\ of\ fish\ in\ air}{weight\ of\ displaced\ water} = \frac{42.2g}{42.1g}$ = 1.00237

- Density of fish = 1.00237 * 0.9998395g/ml = 1.0022g/ml

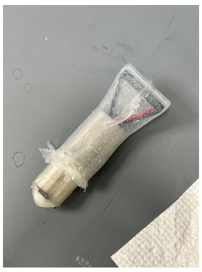
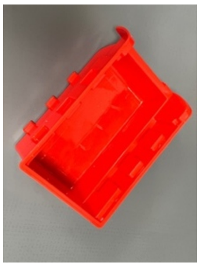



Figure 30: Setup

The density of fish suggested that the fish was almost able to fully submerge under water. This was a good indication because we ought to test the fish when it's fully under water.

1.11. Is the Blue Guppy Fish waterproof?

Various tests were performed to determine whether the silicone mold, the battery cap connection as well as the PLA material was waterproof. Other tests were also used to determine whether hot glue, from a hot glue gun, is waterproof. This was also crucial because the hot glue was applied to firmly attach the silicone mold(skin) to the Blue Guppy fish.

1.11.1. Is battery cap connection waterproof?

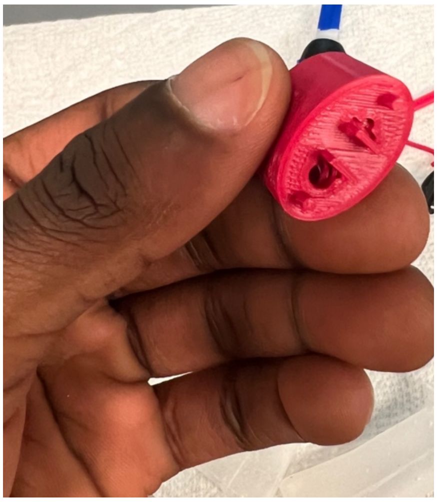


Figure 31: Before sealing bottom holes

Figure 32: Sealed bottom holes

For the waterproofing tests, pieces of paper were placed inside, and the battery box was sealed on both ends and placed inside a water tank for 6 days. As mentioned above, one end was sealed by the hot glue and the other end by screwing the battery cap. The purpose of these tests was to assess both the waterproofing capabilities of the hot glue and the battery cap connection.

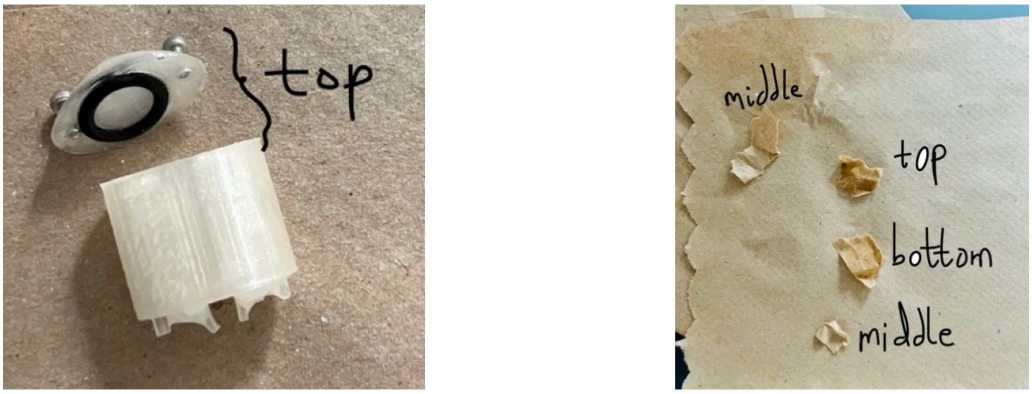


Figure 33: Results of the Waterproofing tests

As from the tests, the fish wasn't fully waterproof. Different conclusions can be derived from these:

- Since the top papers had more wetness than the rest, the battery cap could have perhaps not been screwed properly or not fully waterproof.
- Because PLA material isn't waterproof, 6 days would have been enough for water to diffuse inside the battery box

Based off the tests, it's more likely that the water diffused from the top end to the bottom end and not from both sides. Although the latter hypothesis is also likely, it's clear that hot glue is waterproof and because the setup was placed as it is inside water, there's no reason for the bottom part to not be waterproof, as it encountered more pressure because of depth.

1.11.2. Is skin waterproof?

For testing the skin, it was found out that the skin was waterproof. Hot glue was also applied at the bottom end, and because the setup ended up being waterproof then this results also help justify the hypothesis for the previous tests. This setup was also placed in a water tank for a whole week.

Figure 34: Setup for testing skin waterproof

4. Conclusions.

Thus, the Blue Guppy fish when placed in water together with the silicone mold skin can flap. However, it leans forward with the head because that's where it's center of mass is most close to. Although, the skin was found to be waterproof, there's still doubts as to whether the battery cap connection is waterproof or not. Also, due to results obtained from the underwater tests more design iterations are to be made to enable the propulsion of the fish forward.

5. Future Directions.

This Independent Work serves as a stepping-stone for future iterations of the Blue Guppy Miniature Fish Robot. To make better versions of the Blue Guppy Fish Robot, we plan to make a PCB for easier circuitry of the Blue Guppy, such as switching it ON & OFF. Also, a PCB circuit is also intended for easier regulation of the amount of current that we feed into the motor irrespective of the flapper lengths. This will potentially be implemented using a current-regulated circuit by using opamps and resistors

Also, we plan to add a flexible plastic sheet to the fish tail to enhance latitudinal motion of the fish. This will aid in enabling the fish to move forward which is currently a huge challenge.

Furthermore, more weights can be added around the motor box area to balance the weight of the Blue Guppy fish. Another alternative would be to increase the size of the battery box to add in more space and thus reduce overall weight it displaces in water.

For waterproofing, another idea would be to build a stopper inside the motor box, that only allows the bent shaft to poke out. The remaining area would potentially be glued by a hot glue gun. This would work the same way as the skin, because the skin is critical in covering this part of the fish.

Moreover, as suggested in the introduction, the aim is to build a swarm of robotic fish to effectively study the interactions of schools of fish in fluids.

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