Spring 2021

Elastic Tail Propulsion at Low Re

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ENTITLED

ELASTIC TAIL PROPULSION AT LOW RE

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF

BACHELOR OF SCIENCE
IN
MECHANICAL ENGINEERING

May 28, 2021

Thesis Advisor — date

6/11/2021

Department Chair — date

ELASTIC TAIL PROPULSION AT LOW RE

By

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SENIOR DESIGN PROJECT REPORT

Submitted to
the Department of Mechanical Engineering

of

SANTA CLARA UNIVERSITY

in Partial Fulfillment of the Requirements
for the degree of
Bachelor of Science in Mechanical Engineering

Santa Clara, California

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Abstract

The use of microswimmers, or microscopic swimming robots, in the medical field is becoming more sought after for applications such as targeted drug delivery and microsurgery. While such microswimmers do not yet exist for use on patients, many researchers are working on this front to make them a reality. One of the main challenges in making these microswimmers a reality is creating propulsion in a low Reynolds number environment. This project aims to create and test a prototype of a swimmer which employs 3D circular movement of its tail for propulsion in a very viscous fluid, mimicking a low Reynolds environment in the macroscale. To create a successful proof of concept of 3D circular propulsion, simulations, prototyping, and experimental evaluation of the prototype were conducted during the course of this project. Finite element analysis using the commercial software COMSOL was conducted to design a swimmer tail that would generate a positive thrust force, and a velocity at an order of magnitude consistent with the analytical prediction. Guided by the simulation results, a prototype was fully realized, and testing was conducted resulting in a speed of 0.5 mm/s, which matched with the order of magnitude of the speed obtained from the simulations. The data collected from testing accompanied by simulations confirmed our proof of concept. Lastly, additional simulations were performed to find optimal parameters that can be implemented in the swimmer design for future testing. In essence, this report will provide an overview of the design, construction, and testing of a scaled-up experimental platform to examine the principle of elastic propulsion in highly viscous fluid.

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Chapter 1: Introduction

1.1 Background & Motivation

The rapid development of technology in the 21st century has touched almost every aspect of society. The scientific field of medicine is no exception to this, and every year more and more technological solutions to human health issues arise. Using technology in healthcare will provide a more personalized and precise experience for each patient, bringing more success for every kind of treatment.

Targeted drug delivery is one of the most sought-after advanced treatment methods. The idea is to deliver drugs only to the disease-ridden parts of the body instead of the more common method: giving them to the entire body. One advantage of such an application would be to reduce the side effects of potent, toxic drugs such as those used in chemotherapy. Another advantage would be the possibility of administering a higher dose locally, which may increase the success rate of treatments. Microswimmers, or microscopic swimming robots, are potential candidates for such applications. Furthermore, once these microswimmers are successfully mobilized and controlled in the bloodstream, they may be used to perform a variety of different medical tasks, such as minimally invasive surgery (e.g. dissolving/dislodging a blood clot mechanically), help diagnosing illnesses from inside the body, and even help treating the illness by either delivering the drugs or by applying excessive heat to destroy sick tissues.

However, achieving locomotion in bodily fluids and in vivo environments is no easy feat. In a microscopic environment, the physics of swimming is entirely different that what we are used to in the macroscale. The Reynolds number, which is a nondimensional number that describes the ratio of the inertial forces in a fluidic system to the viscous forces, becomes very low due to the diminished size of the swimmer. A microswimmer swimming in water would feel as if it is trying to swim in a very thick fluid, such as a human trying to swim in molasses or honey. Inertia-based locomotion mechanisms cannot produce forward motion in the very low Reynolds number environment that the small organism experiences [1]. Propulsion methods, such as the tail flapping of a fish, do not work, therefore alternative propulsion methods need to be implemented. Looking to nature, we can see that microorganisms such as bacteria and spermatozoa have found ways to adapt to low Re environments, and using different forms of locomotion, they propel themselves effectively. Taking inspiration from these microorganisms, our project aims to create a swimmer that can successfully propel in low Re environments, and that can help shed light on which parameters will play an important role in determining the swimming performance.

1.2 Literature Review

There is an ever-growing body of literature on locomotion at small scales, featuring analytical, numerical, and experimental studies. As the first step in our project, we conducted a literature review with a focus on experimental studies featuring locomotion at small scale to explore swimming mechanisms that demonstrated successful propulsion, and that we would be able to manufacture with the tools available to us. Furthermore, we wanted to identify a way to wirelessly actuate our choice of swimmer design.

We found that many studies report swimmer tail designs drawing inspiration from bacteria and sperm cells [2-4]. As the fabrication techniques evolved in time, the range of shapes that appear in the literature became diversified [5-12]. Due to its biocompatibility and wireless capabilities, many researchers implemented magnetic actuation. Helical microswimmers of Ghosh and Fischer [13] show how swimmer trajectories can be controlled by external magnetic fields. Li *et al.* [14] and Gao *et al.* [15] deposited magnetic materials onto helical structures to make their magnetically actuated swimmers. DNA-based flagellar bundles combined with magnetic beads are reported in Maier *et al.* [16]. Peyer *et al.* [17] offer an extensive review of the literature on various fabrication and actuation methods of microswimmers, while Gao and Wang [18] report on the advances on targeted drug delivery applications featuring artificial swimmers.

Amongst the designs we found feasible, 3-link swimmer [19], helical swimmers [20], and sinusoidal swimmers [21] can be cited. One way that stood out was to use a sinusoidal swimmer. This swimmer had a tail that moved in a sinusoidal wave so that testing can be uniform as seen in Figure 1.1.

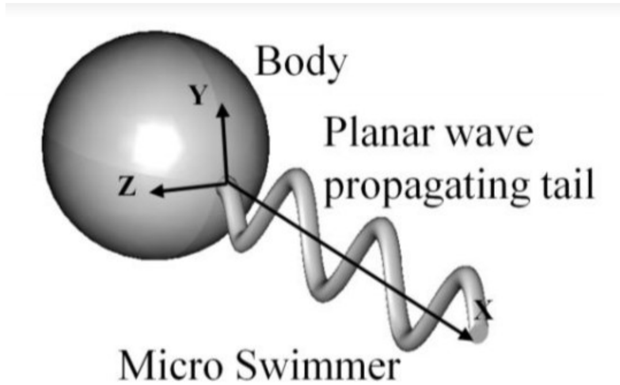


Figure 1.1: Micro swimmer with linearly oscillating tail. reproduced without permission [21]

The next step was to conduct some market research to see what the possible applications of the swimmer could be. This helped our team to determine what aspects of our swimmer we wanted to work on. Since the application of the swimmer in the future would be to deliver drugs throughout the body, looking at market research from Huang *et al.* [22], Miskin *et al.* [23], and Elgeti *et al.* [3] helped establish the following factors to consider in our design:

- Smaller is better so it can go throughout the body without causing damage
- Material needs to be resistant to all fluids (does not corrode)
- Having a mechanism that might be able to work without a motor (most fluids within the human body could damage a motor and make the robot no longer functional)
- Keep manufacturing process in mind (simple enough to be reproduced in large quantities)

Then research was conducted to determine the type of mechanism that would be best to actuate the swimmer's tail. Below are some of the mechanisms considered:

- DC motor to create a circular motion
- Vertical slide-crank mechanism to convert circular motion to a linear motion
- Scotch Yoke mechanism in head to convert a circular motion to a linear motion [21]
- Linear Motor Positioning Stage to be put inside the head
- Magnetically actuated swimmer (magnet in head)
- Acoustically actuated swimmer [26]
- Tail comprised of magnetic beads that are driven by external magnetic field

After investigating the works on swimmer types, actuation methods and how they resonate with the market research, we turned to literature again to study various assembly and set-up types that would help to create an effective tail actuation mechanism. The works of Yu *et al.* [21] and Tabak [20] offered the most feasible solutions. The research by Yu *et al.* [21] is considered for the linear actuation of the swimmer tail, which demonstrates the use of a scotch yoke mechanism to convert the rotational movement of the motor used to a linear movement. We calculated that we could manufacture a scotch yoke mechanism small enough to fit inside of the head of our swimmer based on the preliminary design.

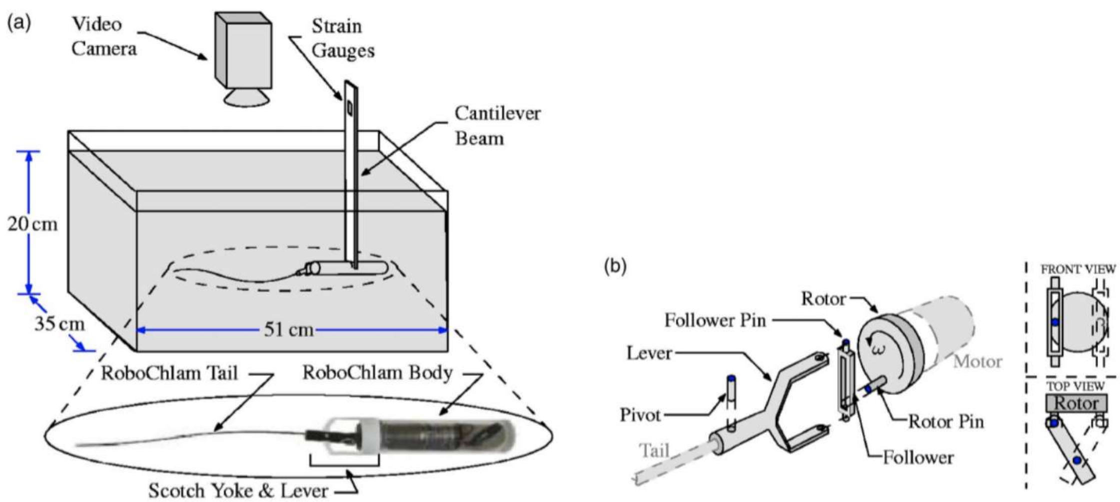


Figure 1.2: (a) Experimental set-up, (b) Scotch yoke mechanism, reproduced without permission [21]

An alternative actuation method we considered, namely the rotation-based actuation, would be achieved by using a mechanism and assembly similar to Tabak's [20]. Tabak demonstrated a robotic swimmer with a silica glass casing. Figure 1.3 shows the main components of the swimmer, while Figure 1.4 shows a breakdown of the electrical components in the head. This swimmer was taken into consideration for our design because it also was on a small scale and all of the components could fit into the head of the swimmer, allowing untethered application.

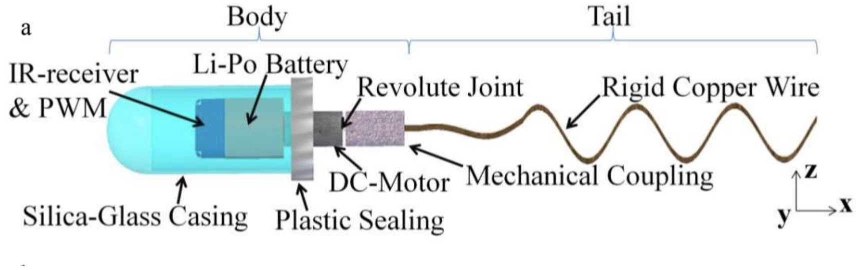


Figure 1.3: Robotic swimmer assembly, reproduced without permission [20]

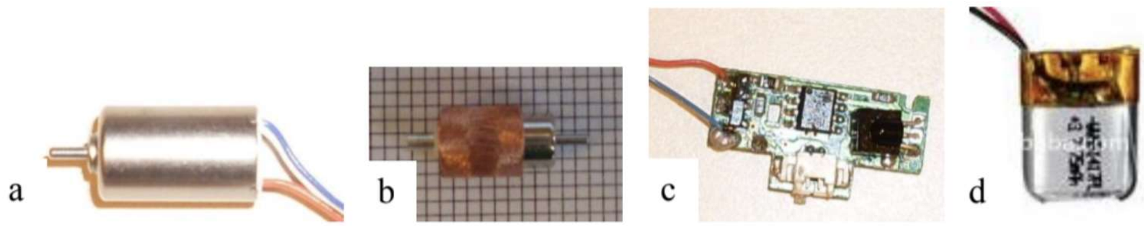


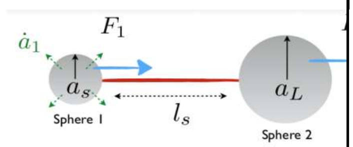
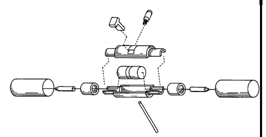
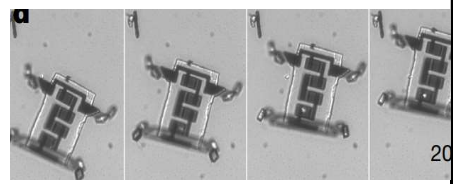
Figure 1.4: Components of actuation system. (a) Coreless DC motor, (b) Windings of DC motor, (c) PWM controller w/ IR-diode, (d) PO battery pack, reproduced without permission [20]

Following the literature review, we concluded that either the scotch yoke mechanism or the rotation-based actuation would be used. We determined that the next step should focus on investigating the components used in constructing various robotic swimmers, understanding how they would fit into our project and how we can effectively utilize them.

1.2.1 Existing Swimmers

In this step of our project, we identified several swimmer designs that would possibly inspire our own. We narrowed them down to three designs that offer components which would fit our design parameters (e.g. small, sealable, untethered). Table 1.1 details these three designs and allows for an easy comparison.

Table 1.1: Identifying Existing Prototypes

	3 sphere swimmer	3 link swimmer	square swimmer (w/ Legs)
Schematic	 [19]	 [24]	 [25]
Length	76.2 mm	60 mm per link 59.9 mm between joints	40 µm
Width	25.4 mm	12 mm diameter per link	70 µm
Thickness	8 mm	2 mm	5 µm
Weight	Not specified in research paper	13.11 oz	5.09 ng
Cost	Amoeba 1.0: $579.53 Amoeba 2.0: $103.17	N/A	Not provided in research paper, however the paper shows plans to mass manufacture these robots
Material	PDMS and EcoFlex 00-10	solid aluminum cylinder & Nylon bushings	Silicon electronics
Motor	No motor; uses a hydraulic system to apply linear motion	1.55V Energizer 309 miniature silver oxide batteries & 6V DC Micromotor	No motor, uses photovoltaics that bias either front of back legs in sequence.

1.3 Project Objectives

This project aimed to create a way to study microswimmer movement in the macroscale, by designing and building a self-propelling low Reynolds number swimmer, which through dynamic analysis could one day be scaled down for use as a microswimmer robot in the future. Building a microswimmer would present challenges that are outside of the scope of this project, however bringing the swimmer to the macroscale allowed us to analyze locomotive methods and quantify a proficient swimmer design, which now can be used as a steppingstone for understanding how to design a microswimmer robot. The challenge presented by this project was to create a swimmer that can swim through a highly viscous medium, meant to mimic the environmental conditions the swimmer would be under if it were a microrobot.

Due to COVID-19 restrictions, the objectives of this project had to be somewhat reimagined to fulfill the goal of analyzing a macroscale micro swimmer's locomotive method. The project evolved to have both a physical aspect and a simulation aspect. Physically, the goal was to create prototypes of two different sinusoidal swimmers, one with 3D rotational motion and one with 2D flapping motion. The main focus for the simulation and testing was for the 3D rotational motion swimmer, with the 2D swimmer as an additional avenue for research. Originally the goal was to have a long testing phase for these prototypes. By testing different frequencies of tail oscillation, an optimal frequency could be found, which was represented by the one that produces the most propulsive force for the swimmer. In the modified version of the project, most of this testing occurred through simulations in COMSOL. The simulations were done as proof of concept of the swimming mechanism, and to test different tail frequencies to determine the optimal frequencies. In addition, another objective for the simulations was to analyze the performance of the swimmer if the offset of the tail was changed to different distances.

Although the testing objective was moved mostly to virtual testing through simulations, the objective of creating the physical prototypes of the swimmer remained. By creating these prototypes, we were able to see if the swimmers produced desired tail oscillations outside of the simulation environment. In addition, small scale waterproofing tests were performed, and a fully realized swimmer design (with electrical wiring and remote-control capabilities) was created.

1.3.1 Physical Swimmer Models

As previously mentioned, two different designs for the swimmer prototype were initially considered. The first was a 3D swimmer, where the tail rotated in a 3D circular motion. The second was the 2D swimmer which had the tail moving in a flapping motion, where part of the design translated the 3D rotational motion of the motor to a 2D movement. The 3D swimmer was the main swimmer for the propulsion study in this project, with the 2D swimmer also being modeled in case time during the manufacturing and experimentation phase allowed for it to be fully realized and tested. Images of the CAD models and detailed drawings for both of these designs can be found in Appendix C.

1.3.2 Overall Project Timeline

The timeline for this project was created as a rough outline for all the different tasks and phases of the project, and in which quarters of the year they were completed. The timeline is included in full in Appendix F.

Chapter 2: System-Level Chapter

2.1 Customer Needs

Since this senior design project was focused on research and no microswimmers currently exist on the market, prototypes were identified by other researchers as "existing products". On the market research side, however, future potential customers were identified which, in turn, guide future researchers on contacts for opinions on future microswimmer applications. The customers considered who might be interested in a microswimmer are as follows:

- Intuitive Surgical
- Boston Scientific
- Stryker
- Mazor Robotics
- Accuray
- Smith and Nephew
- Auris Heath
- Medrobotics

The customer needs are outlined in Appendix D (Table D.1), to reflect the responses obtained from the interview questions, as well as the research conducted on the topic of microswimmers. The "product" which was considered for this table was the swimmer that was designed and created in this thesis.

2.2 Requirements

In the previous section the customer needs and what would be required of the swimmer from a market research point of view was discussed. However, the main goal of our senior design project was to gather research about propulsion in a low Re number environment, and so the requirements for the swimmer system for this project did not coincide with the requirements of the swimmer as a sellable product. With this said, the requirements used as benchmarks for the project were related to the swimmer as a research model and established what criteria needed to meet in order for the swimmer and project to be successful.

There were a number of design parameters in the swimmer system. In order to better guide the design and set requirements for the system, a dimensional analysis on our desired (and measured) output was performed. For this analysis the propulsion speed was used as the output (which was the swimmer output measured). Propulsion speed is dependent on fluid density, fluid viscosity, swimmer length, how fast the tail is rotating, and the bending stiffness of the tail, as seen in Equation 1.

$$U = f(\rho, \mu, L, \Omega, A) \tag{1}$$

By performing a dimensional analysis, the number of independent variables was reduced and the dimensionless relationships between the now dimensionless propulsion speed as a function of two dimensionless groups was obtained, seen in Equation 2.

$$\frac{U}{L\Omega} = f\left(\frac{\rho\Omega L^2}{\mu}, \frac{\mu L^4 \Omega}{A}\right) \tag{2}$$

The first dimensionless group is really the Reynolds number shown again in Equation 3, or the ratio between inertial force of the system and viscous force of the fluid.

$$Re = \frac{\rho\Omega L^2}{\mu} \tag{3}$$

The second relevant Pi group is what is known as a sperm number, which is a comparison of viscous force acting on the filament (tail) and the elastic force of the filament itself shown again in Equation 4.

$$Sp = \frac{\mu L^4 \Omega}{A} \tag{4}$$

The sperm number determines what is the deformation across the tail, with the fluid force trying to deform it and the elastic force trying to resist it.

The dimensionless analysis showed that the Reynolds number is a relevant dimensionless group meaning it should be conserved between the microscopic environment and the simulated environment. In order to achieve this conservation, a fluid environment with a low Reynolds, in the order smaller than 1, needed to be created. This was achieved by utilizing corn syrup as the testing fluid. The high viscosity of corn syrup brought down the Reynolds number to the required level, and its translucent quality was crucial during the experimental phase.

In addition to the Reynolds number, the dimensional analysis performed also gave the sperm number as a dimensionless group which needed to be considered. In order for the propulsion subsystem to induce sufficient elastic deformation in relation to the viscous forces, it was determined that the sperm number should be at least in the order of 1. In order to achieve the desired sperm number, a guitar string was used as the elastic tail filament.

With variables in both of the subsystems detailed, it was verified that with the use of corn syrup as the testing fluid and a guitar string as the elastic propulsion element, a Reynolds number around 0.5 and a sperm number around 2 were obtained, which satisfies the requirements for these two subsystems.

2.3 System Sketch

Theoretical testing, and the understanding of how a swimmer behaves in a highly viscous environment, was determined to be the main function of the swimmer. Figure 2.1 sketched the swimmer in its entirety. The scenario for this swimmer was for it to be used in a lab, by students and professors who want to learn more about locomotion in environments similar to microscopic ones. This model produced a stepping-stone in understanding the future microswimmer development.

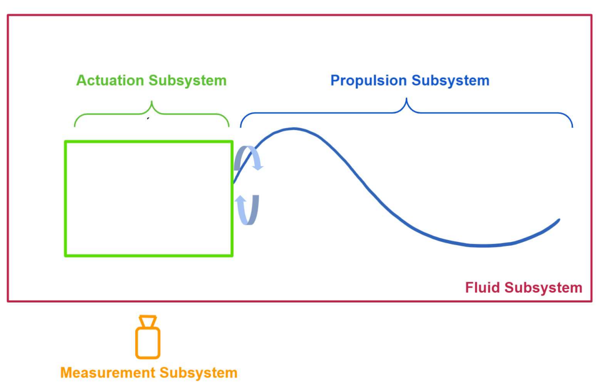


Figure 2.1: A basic sketch of swimmer in tank

2.4 Functional Analysis

The primary function of a microswimmer is to be able to swim in a very viscous environment so that it can maneuver inside the human body. A fundamental characteristic of a swimmer lies in its non-invasive treatment methods. With this essential function, the swimmer's sub-function serves as a future product for targeted drug delivery and any other less invasive options for treatment. Other key sub-functions include tasks such as telemetry, breaking down fatty lipids, and being able to analyze information and transmit it externally.

There are some constraints we had in our design and testing. One constraint was the size of our swimmer. Since we planned to work in our advisor's lab, the team was restricted to a tank that could fit in the lab space. This meant that our swimmer had to be small so that it would be far enough away from the walls of the tank so that the force of the fluid on the walls would not have a significant effect on the motion of the swimmer (boundary effect). Also, the design had to be fairly simple so that it wouldn't be too difficult to construct within the time allotted, one school year, to conduct testing and redesigning if needed. We were not able to send parts out for manufacturing, so we made sure the swimmer was designed to be built with the skill sets our team already had and only used tools we had available to the team in our Advisor's lab and the Machine Shop.

Potential opportunities for improvement are as follows:

- Creating a smaller design (the smaller the better so it can go throughout the body without causing damage)
- Material is resistant to all fluids (does not corrode)
- A mechanism that might be able to work without a motor (most fluids within the human body could damage a motor and make the robot no longer functional)
- Keep manufacturing process in mind (if this is to be a product in the future the manufacturing process needs to be simple enough to be reproduced many times).

2.5 Key System-Level Issues

Anchored vs Free Swimming

Ideally, the swimmer was designed to swim freely without being attached to anything. To make this happen we had to make sure the size and weight of the swimmer were equivalent to the buoyant force, such that the swimmer did not quickly sink to the bottom or float to the top. If we were able to achieve this, we would be analyzing the speed or displacement of the swimmer. However, if we were not able to design a swimmer that can swim freely our next option was anchoring it to a fishing line inside the tank. For this design, we would be analyzing the propulsive force or speed resulting from the swimmer.

Measurement Methods

The measurement method was determined by the type of swimmer design as mentioned previously. For the case of a non-anchored swimmer, the speed and displacement would be measured. This was done by setting up a video camera perpendicular to the swimmer's direction of motion, and there would be grid lines behind the swimmer so we could easily see the magnitude of its displacement. For the case of an anchored swimmer, we would be looking at the propulsive force of the swimmer. This would be done by attaching the swimmer to a cantilever beam while using strain gauges to calculate the force on the beam.

Scaling Down

One important parameter taken into consideration was the ability of our design to be scaled down to a microscopic level. With this in mind, the design had to be simple because making a microswimmer with lots of moving parts would be difficult to scale-down. However, scaling parts such as the motor and battery were not taken into consideration since the motion of the microscopic swimmer would be actuated using different methods. Another aspect to keep in mind was how the scaling down could affect the type of data and analysis collected/conducted. For example, this leads to the conduction of extensive dimensional analysis on the swimmer so it could be compared to a micro swimmer in the future.

Waterproofing Methods

The head of the swimmer needed to be waterproofed in order to protect the motor, battery, and other electronics inside the head. To solve this issue, we designed a swimmer that uses magnets to connect the tail on the outside of the head to the motor and crank on the inside of the head.

Propulsive Method

A flexible wire tail was used for our swimmer, so the next step was to determine if the swimmer would have a linear or rotational motion for the tail. Initially, we were considering linear motion, that would be achieved by using a scotch yoke mechanism that would turn rotational motion from the motor into linear motion. However, this method was found to be difficult to incorporate into our design due to problems with fitting all the necessary pieces into the head while still keeping it waterproof. So, rotational motion was chosen, and it was found that this method was much more compatible with the parameters of our design.

2.6 Subsystem Breakdown

The swimmer can be broken down into four main subsystems. The first subsystem is the propulsion system, which produces the physical forward motion to move the swimmer through the fluid. The second is the control subsystem, which controls the operation of the swimmer remotely. The third is the fluid system, which makes up what the swimmer is immersed in for testing. And the fourth is the measurement subsystem, which tracks the movement of the swimmer so that its performance could be assessed.

2.7 Team and Project Management

Since the swimmer was constructed over a year from September 2020 to June 2021 there were some constraints that were faced in our design and testing. Other than the constraints listed in the Functional Analysis section, there were also some constraints due to things outside of our design. The main constraint was due to COVID-19, where we were not able to go into the lab or work on the project at the same time. Due to this constraint our team split the work of designing, prototyping, simulating, and testing. Preliminary prototyping and simulations were conducted outside of the lab.

The schedule for Fall, Winter, and Spring is specifically laid out in Appendix F. Our team also used a combined PowerPoint slide and had regular meetings with a notes system to keep track of weekly tasks.

An estimated budget can be seen in Appendix G. This budget was estimated based on the expenses of the components needed for both 3D and 2D designs. These estimates were gathered with the help of our advisor.

To test the swimmer design, our team determined we would need a tank of some sort of viscous fluid and parts to realize the physical swimmer. The tank needed to have a volume of ~36,000 cm^2. The swimmer components required at least a motor, head casing, and tail. More robotic components were needed to be purchased for the electrical system and waterproofing of the swimmer. Our team also planned on using a strain gauge or other device (such as a video camera) to measure the speed and thrust of the swimmer. All these components were included in the "Various Robotics Components" section seen in the table in Appendix G.

There are a couple of minor safety risks included in our project. Most of these safety risks were the same as any other robotics projects, such as use of batteries, soldering, and bonding agents. All of these were mitigated mostly through wearing appropriate PPE, such as long sleeves and pants, gloves, face masks and safety goggles. Extensive explanations and mitigations of these safety risks are included in Appendix L.

Each member of our team had assigned roles and responsibilities, to make sure that our progress was as efficient as possible. The roles are seen below:

- Rafaela Barreto: Secretary. Responsible for taking notes during all group meetings, as well as scheduling meetings between different members of the group.
- Yoel Park: Corresponding Secretary. Responsible for all the communication between our advisor and the team.
- Jennifer Miranti: Weekly reporter. Puts together the team's report for our weekly meetings.
- Elijah Vidal: Facilitator. Make sure we are on track during our meetings.

Chapter 3: Subsystems Chapter

As mentioned in the systems level chapter, our design consists of four subsystems: the actuation system, propulsion system, fluid system, and measurement system. These four subsystems work together in order for the design to be complete; with the correct fluid environment to mimic the microscopic world, the mechanics necessary to propel the swimmer forward, and the analysis tools required to characterize and judge the motion of the swimmer.

3.1 Actuation Subsystem

The main purpose of the actuation subsystem is to drive the swimmer's tail in a circular motion. In order to achieve this, certain components were needed. One of those is a dc motor with enough torque to rotate the tail in such a viscous environment. A 3 Hz motor was settled on to fit this requirement. To power and control the dc motor wirelessly a microcontroller was needed as well as a battery and transistor to complete the circuit, all wired on a protoboard. The wiring for the actuation system can be seen in Figure 3.1. Additionally, Table 3.1 details the components in the actuation system, their dimensions, and manufacturers.

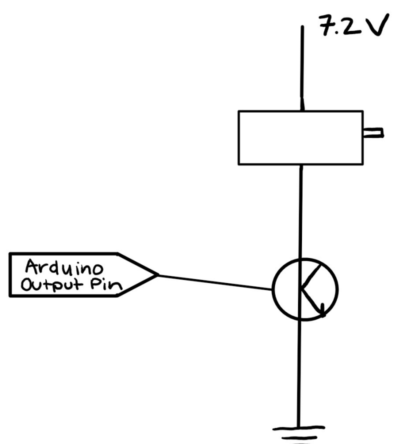


Figure 3.1: Wiring diagram for swimmer prototype

Table 3.1: Actuation Subsystem Components and Manufacturers

Component	**Dimensions**	**Manufacturer**
Dc Motor (3 Hz)	15.2 mm x 12 mm x 10 mm	Geartisan
Microcontroller - Arduino Nano 33 IOT	45 mm x 18 mm	Arduino
Battery	11.5 mm x 31.0 mm x 3.8 mm	Adafruit Industries LLC
TIP 122 Transistor	N/A	Bridgold
Protoboard	Cut into 14 mm x 9 mm	SparkFun Electronics

The microcontroller chosen for this actuation system was the Arduino Nano 33 IOT. This microcontroller can be controlled via Wi-Fi, specifically through an Arduino webpage created by our team which allows for complete remote control of the swimmer. Remote actuation means testing will be greatly facilitated since it will allow for the swimmer to remain in the tank between trials.

Figure 3.2: The Arduino Nano 33 IOT, which helps to remotely control the swimmer

3.2 Propulsion Subsystem

The main goal of the propulsion subsystem is to produce the physical forward thrust to move the swimmer through the fluid. The swimmer needs to have elastic deformation in order to create the thrust in the viscous fluid. Referring to the Pi groups established through dimensional analysis, one requirement that needs to be satisfied is a varying sperm number. We can conform to this requirement by allowing the tail to be made different lengths for different trials, which can increase and reduce the sperm number of the swimmer. Changing the rotational frequency of the tail can also increase and reduce the sperm number and give us even more room to work with. It is important to note that changing the bending stiffness of the filament would also have an effect on the Sperm number, however we will be using one single material for the tail so this material property cannot be varied between trials.

In order to satisfy the desired sperm number a guitar string was used as the elastic tail filament. The guitar string's bending stiffness of 2 Pa·m^4 paired with the high viscosity of the fluid resulted in a suitable sperm number. The sperm number also showed that the length of the filament should be around 10 cm the rotational offset should be around 8 mm and an angular frequency around 3 Hz.

Figure 3.3: Guitar strings; the material likely to be used as the elastic filament for the tail "used without permission" [1]

The next requirement for the propulsion subsystem was finding a way to have the tail rotate in the fluid while keeping the motor and electronics dry and away from the fluid. To protect the electrical components, we sealed them in the body of the swimmer using an O-ring and a cap that was screwed on with four fasteners. To transfer the rotation from the motor and crank on the inside of the body to the tail on the outside magnetic coupling was used.

On the inside of the swimmer, there is a magnet attachment on the pin of the motor. This attachment houses up to 4 neodymium magnets, which will spin with the motor (Figure 3.4). Once the swimmer is closed, the inside magnets are coupled with polar opposite magnets on the outside. These magnets will have an elastic filament, acting as a tail, attached with epoxy putty. Figure 3.5 shows the magnets on the inside and outside of the body, the outside magnet equipped with the tail. This successfully transmits rotation from the inside of the swimmer to the elastic filament on the outside, propelling the swimmer forward.

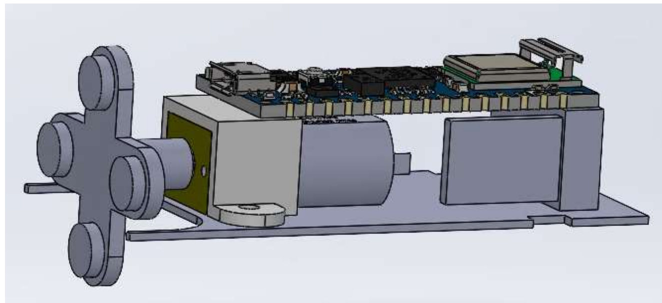


Figure 3.4: Magnet attachment on pin of motor, slider piece also pictured

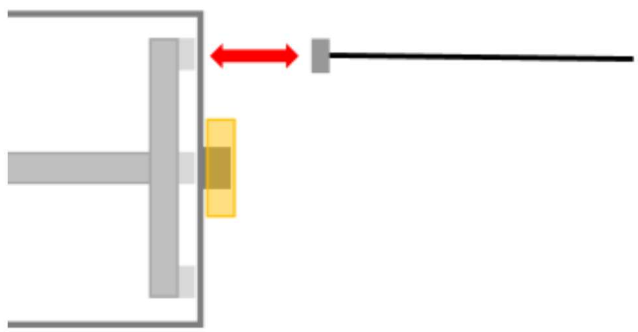


Figure 3.5: Illustration of the magnetic coupling

3.3 Fluid Subsystem

The fluid subsystem encompasses the medium in which the swimmer is moving in. This subsystem relates to the buoyancy of the swimmer and will be taken into account when determining the size of the swimmer, as set forth by the design requirements. The dimensionless analysis showed that the Reynolds number is a relevant pi group and so it should be conserved between the microscopic environment and our own simulated one. In order to achieve this conservation, we needed to create a Low Reynolds number environment, smaller than 1 order of magnitude. We plan on achieving this by utilizing corn syrup as the testing fluid. The high viscosity of corn syrup helps to bring down the Reynolds number to the required level, and it has a translucent quality which was crucial during the experimental phase.

Figure 3.6: Highly viscous corn syrup, reproduced without permission [6]

Initially silicone oil was considered for the fluid system because it has a very high viscosity as well. However, it is very messy and difficult to clean up outside of a lab (if the lab space could not be used), so since we were running the experiments outside of the lab it was more feasible to use corn syrup.

3.4 Measurement Subsystem

The goal of the measurement system is to take data for different trials of the swimmer and help characterize the movement of the swimmer's tail. To measure the dislocation of the swimmer, a video camera will be set up outside the tank and record each run of the swimmer. A tape measure will be placed on the back of the tank, so that the distance traveled by the swimmer can be easily seen in the video. Since the time of each swimming trial will be recorded, this dislocation will be converted into swimmer speed.

Chapter 4: FEA & Simulations

Before the prototype was built and physical testing was conducted, simulations were used to confirm that the current parameters would produce a swimmer that propelled forward. It is important to note that these simulations focused on the 3D swimmer design. This was because there was more literature review on it which proved that it could have a greater success rate. The 2D swimmer design could be later analyzed in future work.

4.1 Simulations

All of the simulations were conducted with Finite Element Analysis implemented through the software COMSOL. Since it is computationally heavy to simulate the entire swimming motion, it was decided to first focus on predicting the propulsive thrust generated by the swimmer when it is held stationary.

There were two approaches that could be taken when creating the movement of the tail. The first was to use a stationary fluid with the tail rotating as seen in Figure 4.1. However, this is rather computationally expensive. Not only would the simulation take a long time to run because of the small time step and dense mesh required, but it also would take a lot of CPU power.

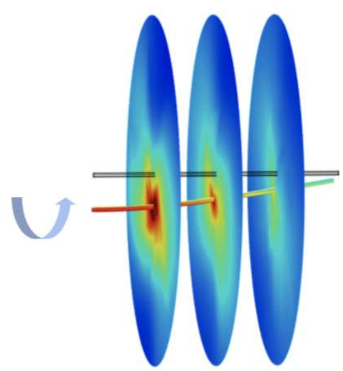


Figure 4.1: Stationary fluid with rotating tail simulation model

Alternatively, a change of reference frame can be performed to rotate with the filament. This creates a rotating flow around the filament, but the one end of the tail is now fixed, and the filament will develop steady deformation in the rotating fluid as seen in Figure 4.2. This will output the same results, but will be computationally more efficient, so the second method was chosen.

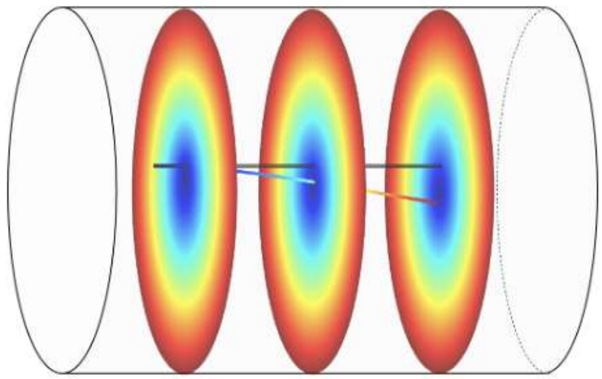


Figure 4.2: Stationary tail with rotating fluid simulation model

The full model consisted of a cylindrical filament to simulate the tail and a cylindrical outer boundary domain to simulate the domain of the viscous environment. When setting up the COMSOL software, the continuity and Stokes equations seen in Equations 5 and 6 were set as the governing equations.

$$\nabla \cdot \mathbf{u} = 0 \tag{5}$$

$$\mu \nabla^2 \mathbf{u} = \nabla p \tag{6}$$

These equations help describe how the values of the unknown variables change when a known variable changes.

To make sure that the data was as accurate as possible, only one variable was changed in the simulation at a time. Table 4.1, 4.2, and 4.3 displays the main parameters used when conducting the simulations.

Table 4.1: Fluid Parameters

Density	1,400 kg/m^3
Dynamic Viscosity	3.18 Pa s

Table 4.2: Tail Parameters

Bending Stiffness	2 Pa m^4
Young's Modulus	2.8 x 10^9 Pa
Poisson's Ratio	0.4

Table 4.3: Simulation Dimensions

Radius of Filament	8 mm
Length of Filament	100 mm
Radius of Domain	1,000 mm
Length of Domain	15,000 mm
Frequency	3 Hz

To mimic the motion of the tail as close to real life as possible, several boundary conditions were set. The first boundary condition was to fix one end of the filament, while the rest was free to interact with the fluid as it rotated. This simulated the end of the tail that would be fixed to the motor. Then a rotating channel wall was placed on the boundary domain with an imposed rotating background flow at a rate of Omega. The other two walls at the ends of the boundary domain had open boundary conditions so that there would be no external forces acting on the filament.

The simulation consisted of a 2-step process. The first step consisted of a stationary step, which created a steady state rotating flow. The second step was a time dependent process which evaluated the deformation of the filament as it is subjected to the rotating flow. We used the "Multifrontal Massively Parallel Sparse Direct Solver" (MUMPS) and the model was fully coupled. This makes it so whatever happens to the flow affects the solid and vice versa.

The first simulations generated used the automatic mesh that COMSOL generates as a "physics controlled" mesh option. However, the data produced was significantly different than anything seen in the literature review. As can be seen in Figure 4.3 all of the data is scattered and there seems to be no convergence. This is because the auto mesh is very coarse and COMSOL automatically controls where the mesh is more or less dense. However, our simulations did not need to take into account the flow solution near the channel walls, just near the filament.

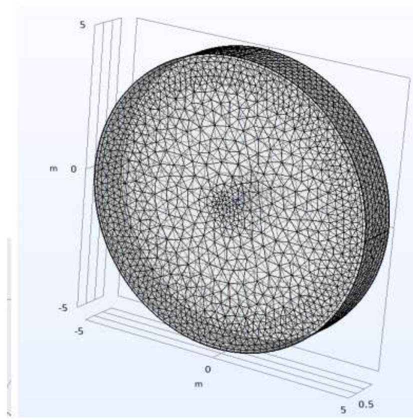


Figure 4.3: Auto-mesh from COMSOL

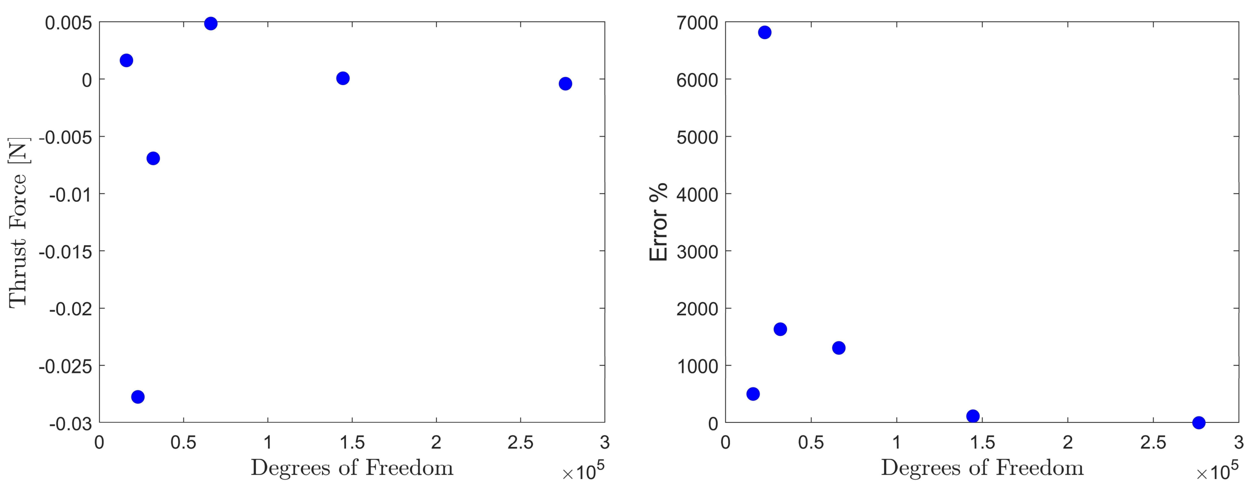


Figure 4.4: Auto-mesh force results and the percentage error

To create a mesh that better suits the original swimmer design, and that focuses on the solution on/near the filament, a mesh convergence test was conducted. Using the technique of Mesh Convergence, the true mesh for the model was found, as can be seen in Figure 4.5. In order to better resolve the fluid-structure interaction around the filament, a local mesh refinement was applied in the vicinity of the filament, as seen in Figure 4.6. This mesh was much finer than the automated mesh, and it packed more elements on/near the filament so that a better solution could be generated.

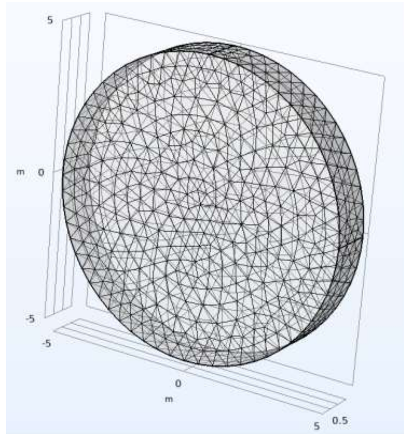


Figure 4.5: Custom mesh created in COMSOL

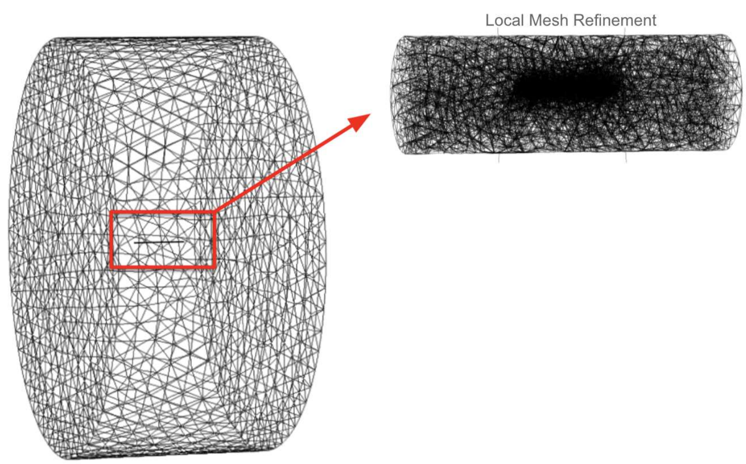


Figure 4.6: Local mesh refinement around the filament

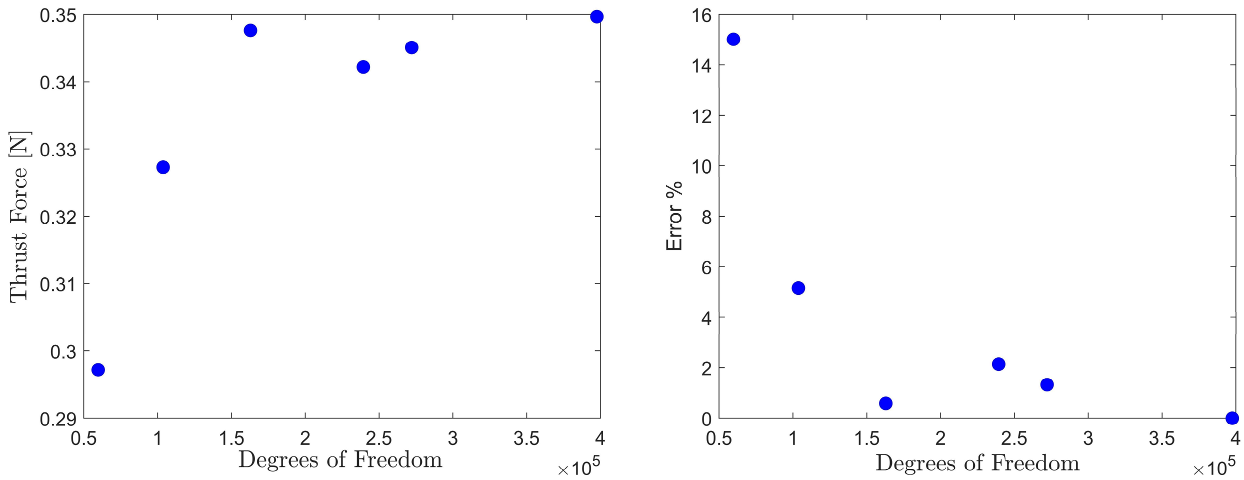


Figure 4.7: Custom mesh force results and the percentage error

Using Equation 7 it can be seen that the auto-mesh had a best-case scenario error to be 116%, while the custom mesh had a worst-case scenario error to be 15%.

$$\%Error = 100 \left| \frac{Force\ at\ highest\ DOF - Force}{Force\ at\ highest\ DOF} \right| \tag{7}$$

This meant that the simulations using the custom mesh were extremely more accurate than with the Auto Mesh.

After the mesh was set, the simulation was performed which obtained the deformation along the filament and the flow field around it. The hydrodynamic traction was then calculated and integrated over the surface of the deformed filament using Equation 8 to obtain the propulsive thrust of the swimmer.

$$F = \int_A (\sigma \cdot \mathrm{m})_x \, dS \tag{8}$$

With the parameters discussed previously, the simulation predicted a propulsive thrust of -1.5 mN. The negative sign indicated that the swimmer propelled in the negative x-direction. Based on the propulsive thrust predicted by the simulation, the order of magnitude of expected swimming speed that should be expected in the physical testing was found. To estimate the speed, the trust generated using Equation 9 was balanced with the drag experienced by the swimmer using Equation 10.

$$F \approx -1.5\, mN \tag{9}$$

$$Drag \approx 6\pi\mu aU \qquad (10)$$

The drag of the swimmer was estimated by approximating the swimmer body as a sphere with radius 50 mm as seen in Figure 4.8.

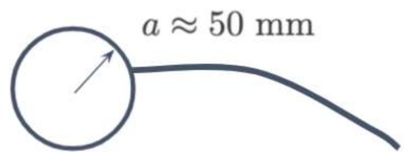


Figure 4.8: Approximation of swimmer used for preliminary calculations

Applying the drag formula and putting in the value of propulsive thrust from simulation, the propulsion speed was estimated to be in the ballpark of 0.5 mm/s.

Chapter 5: Detailed Design & Manufacturing

Through simulations, it can be seen that there is an expected forward thrust for the 3D swimmer modeled. This opens the door for the next stage of the design process, which is the detailed design of the swimmer prototype. All the different parts of the detailed design are mentioned in Chapter 3 (subsystems chapter).

After different iterations of the swimmer model shown in the introduction, the final exploded view of the swimmer CAD model can be seen below, with the relevant subsystems annotated.

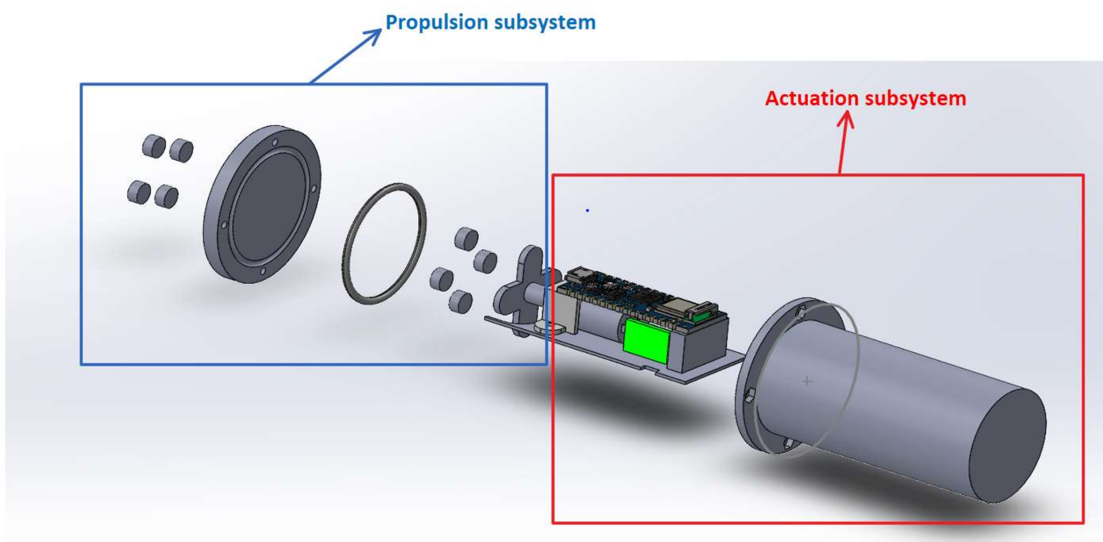


Figure 5.1: Final model of swimmer, 3D design

5.1 Prototype Manufacturing

The majority of the parts for the swimmer were made with 3D printing, which allowed for rapid prototyping and gave room for tweaking the design in order for it to work exactly as intended. For this project, the 3D printer used was the flashforge finder, with PLA plastic as the printing material. For the main swimmer design, the body, slider piece with magnet attachment, and lid were all 3D printed. The figures below show the 3D printed components separately and the final prototype ready for testing.

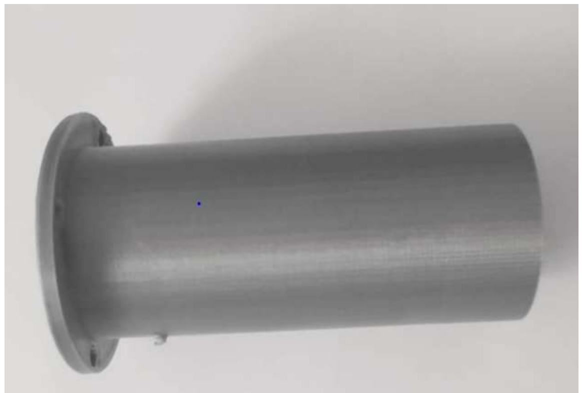


Figure 5.2: 3D printed swimmer body

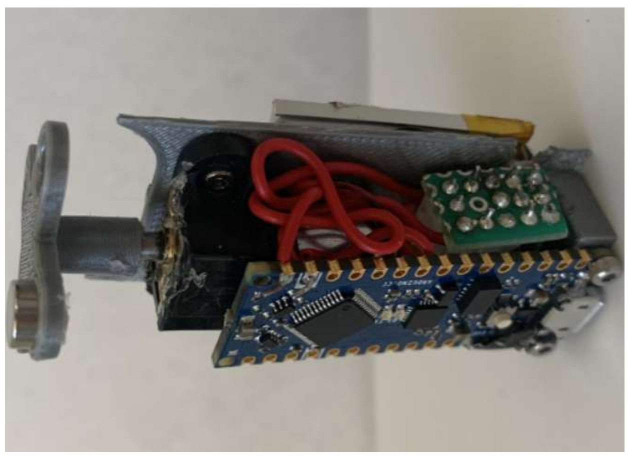


Figure 5.3: 3D printed slider piece and wired components for the actuation subsystem

Figure 5.4: 3D printer swimmer lid

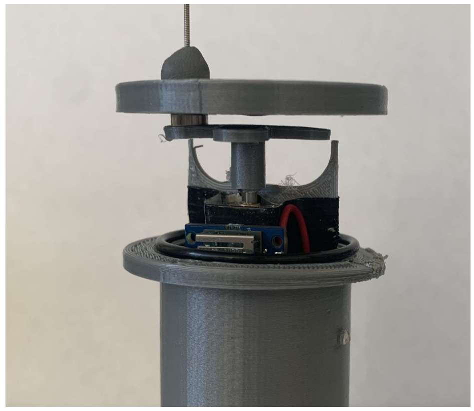


Figure 5.5: Magnetic coupling on the realized prototype (slider piece lifted out for easier viewing)

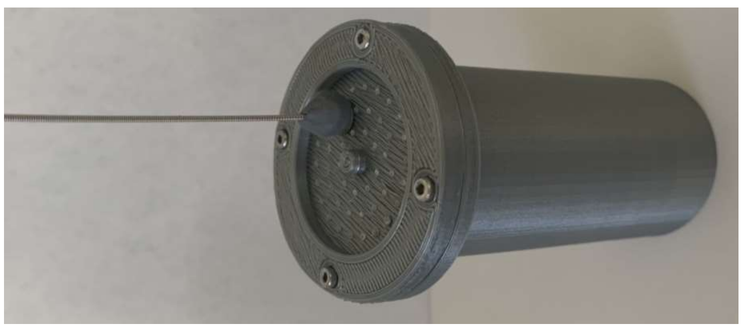


Figure 5.6: Swimmer prototype fully assembled

5.2 Buoyancy Considerations

An important consideration that has not been detailed in this design is that of the buoyancy of the swimmer, to ensure it does not sink or float up to the top of the tank during testing. In order for the swimmer to be neutrally buoyant, the weight of the swimmer needs to be equal to the buoyant force. However, calculations conducted utilizing Equation 11 below revealed that the buoyant force on the swimmer is greater than its weight. Around 33 g of extra weight needed to be added to the swimmer in order for it to be neutrally buoyant. In order to accomplish this, a weighted putty was placed on the outside of the swimmer to make up the extra 33 g, and with this, the swimmer became neutrally buoyant.

$$F_{buoyancy} = \rho_s V g > F_{weigh} \tag{11}$$

Chapter 6: Testing and Results

6.1 Experimental Setup

In addition to building the swimmer, to complete the testing of the prototype, a testing environment also needed to be created. This testing environment was made up of a 40-gallon tank, measuring 91 cm in length. This tank was filled with 20 gallons of corn syrup, the viscous fluid of choice to create a low Reynolds number environment. As discussed previously, the buoyancy of the swimmer was taken into consideration, and weighted putty was added to the swimmer's body in order to make it neutrally buoyant.

To account for any residual imbalance in buoyancy, a guide rail was used. This guide rail was made up of thin fishing line attached to wooden dowels on either side of the tank. The swimmer's body was fitted with two hooks which attached to the fishing line and guided the swimmer's movement in a straight direction. This setup also includes a measuring tape on the back of the tank, which will assist in data collection. The tank testing setup can be seen in Figure 6.1.

Figure 6.1: Swimmer inside the test ready tank

6.2 Obtaining Data

Once the swimmer prototype was fully realized and an experiment setup was created, the last step was to place the swimmer in the tank of corn syrup to run tests and collect data. The desired output for the data collection was swimmer speed and for the physical testing, the manipulated variable was tail length.

Videos were taken for each run of the swimmer in the tank, and average propulsion speeds were obtained using these videos. For each run the time taken for the swimmer to travel a fixed distance of 20mm was recorded. Then, speed was calculated utilizing Equation 12. Three trials were done for each swimmer in order to obtain an overall average speed for each tail length.

$$\langle U \rangle = \frac{\sum_{i=1}^{3} \left({\Delta x_i}/{T} \right)}{3} \tag{12}$$

6.3 Data & Results

For the physical tests, trials were run for swimmer tail lengths ranging from 25 to 105 mm. With a rotation frequency of 3 Hz, the elastic filament is able to generate sufficient deformation to propel the swimmer forward. The final collected data can be seen in table 6.1. The speed values obtained from the experimental tests are within the same order of magnitude as the speed value from the simulations. The experimental results were also plotted, seen in Figure 6.2.

Table 6.1 Experimental Data on Effect of Tail Length

Tail Length (mm)	**Distance Traveled (mm)**	**Time (s)**	**Speed (mm/s)**
25	20	116	0.17
45	20	69	0.29
65	20	63	0.32
85	20	52	0.38
105	20	40	0.50

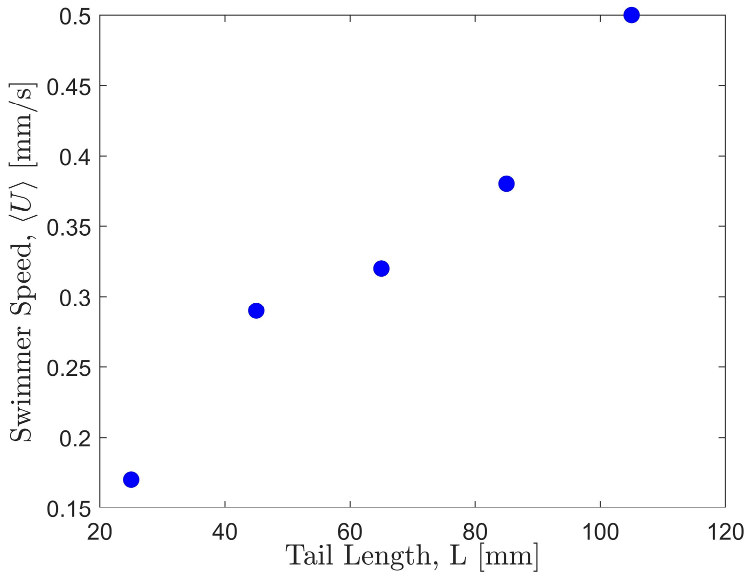


Figure 6.2: Experimental data plotted, showing positive correlation between speed and tail length

As can be seen in the plot, the propulsion speed monotonically increases with the length of the tail, reaching a maximum of 0.5 mm/s for a tail length around 100 mm. This represents a successful proof-of-concept on how to generate elastic propulsion in a low Reynolds number environment.

6.4 Further Simulations

After it was determined that the swimmer prototype was generating a forward motion similar to the calculations obtained from the initial simulations, the next step was to determine the optimal parameters. Force vs. Frequency tests were conducted to determine what the optimal parameters to use moving forward.

The frequency that the filament was moving at was changed, in order to determine what frequency would generate the most force. When looking at frequencies ranging from 0-50 Hz, in Figure 6.3, it can be seen that there was a peak to where the frequency produced the most force. Originally, the prototype's motor was spinning at a frequency of 3 Hz. From the simulations, it was clearly seen that if a motor with a frequency of around 25 Hz is used, this will give the swimmer that most amount of force, which means that it would move faster in the viscous fluid. However, it is important that the frequency is not increased further because as seen in Figure 6.3, there is a peak to the Frequency vs. Force curve and if the motor exceeds 25 Hz, the force will decrease.

The main limitation for the physical prototype design was that the swimmer needed to be as small and compact as possible. However, smaller motors spin at a lower frequency.

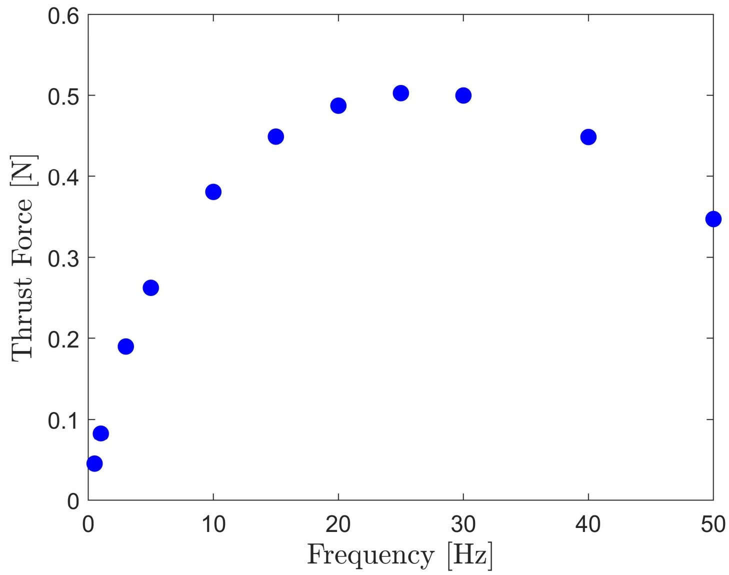


Figure 6.3: Force vs. Frequency data from COMSOL

Conducting these simulations of Force vs. Frequency produced the optimal parameters for the swimmer. Moving forward with the design, these are the types of parameters that would need to be implemented to produce a swimmer with the most trust force. Also, it would be beneficial to address the limitations stated above so that the parameters can be further changed to see if that will increase the thrust force of the swimmer.

6.5 2D Swimmer Testing

As mentioned previously, a 2D swimmer with a flapping motion was also modeled, as another option for testing. The 3D swimmer was focused on for simulations and the bulk of testing, since through literature review it seemed to be a more frequently used design and therefore would most likely produce better results. The 2D design was also realized as a prototype, however it was unsuccessful during testing, and did not produce any forward movement.

Chapter 7: Cost Analysis

Before starting the build for the prototype, the overall cost for the entire swimmer system was estimated to be about $700.00. This included approximately $200.00 for the propulsion system, composed of the motor and its powering components, and the control system, composed of the parts that allow for control of the swimmer, such as the Arduino microcontroller. In addition to the prototype's cost, a large part of the estimated budget, $500.00, was attributed to the fluid system, which included the tank that the prototype was tested in and the testing fluid itself (initially silicone oil). The bill of materials for the fully actualized swimmer prototype can be seen in Appendix G (Table G.2).

With all of these components, the overall cost of the swimmer prototype comes to $523.52, which is under the initial estimated budget. The initial budget was overestimated to ensure no materials would be lacking, but the largest contribution to the lower actual cost is due to the fact that corn syrup was used as the swimmer fluid instead of silicone oil. This choice was made because due to lack of access to a proper lab space, corn syrup would be a more manageable testing fluid for an at-home experiment.

Chapter 8: Patent Search

The main purpose of completing this patent search was to explore current patents and identify any existing patents that may be similar to our project. Additionally, we looked over several patents that may be useful for our design. There were no specific patents that had been previously published regarding swimming at low Reynolds numbers, so we decided to move forward with our invention.

8.1 Invention Description

Title of Invention: Macroscale Microswimmer Robot with Magnetic Tail Actuation for Waterproofing

Inventors: Rafaela Barreto, Jennifer Miranti, Yoel Park, Elijah Vidal (Oct. 22, 2020)

As previously explained, in order to study microswimmer, and specifically to understand their propulsion in the microscale, it is helpful to create a macroscale version of the swimmer. This robot will attempt to swim in a highly viscous fluid, in order to mimic the microscopic environment of the microscale. With this in mind, our invention is a macroscale model of a microswimmer. This swimmer is composed of a main body, lid, tail attachment, and inner mechanics slider. The main body of the swimmer housed a sliding piece which included a microcontroller (in addition to the motor and protoboard with all necessary wiring) which allowed the swimmer to be controlled remotely. This made the process of testing the swimmer a lot simpler, since the swimmer did not have to be taken out of the fluid to be turned on or off, or to change the motor's frequency.

One of the main challenges of making a swimming robot for this purpose was finding a way to keep the electrical elements out of contact with the fluid in which the test is being conducted. The inner workings of the swimmer needed to be protected from the outside fluid, but the motor movement inside the swimmer had to translate to the outside in order to oscillate the swimmer's tail. To solve this problem, the invention proposed uses magnets in order to translate the motor motion to the tails, attached to the outside of the swimmer body.

A clover-shaped, 4 arm attachment was placed on the motor's pin, with housing spaces for 4 neodymium magnets can be seen in Figures 1 & 2. Once the lid of the swimmer is fitted, the tail attachment, a circular piece with housing spaces for four additional magnets, as seen in Figures 3

& 4, is placed on the face of the lid. The 4 pairs of magnets formed a strong connection, and when the motor is actuated, the tail attachment on the outside of the swimmer follows its movement. The tail can be attached straight to the magnet on the outside of the swimmer (on the tail attachment piece). A major benefit to this waterproofing method is that different swimmer tail attachments can be used with the same swimmer body. All that is needed is a tail attachment for the type of tail being tested (such as straight filaments or flat sheets, for example) and it will attach and detach with ease to the main lid.

8.2 Sketches

The sketches for the patent can be found in Appendix I.

8.3 Possible Patent Classifications

The first classification that is important to have for our swimmer is Class B25B, Subclass 11/00. This class has to do with magnets, which is important in our patent because it is the way that our team has created to be able to make our swimmer waterproof. The subclass has to do with magnetic work holders which is also very important to our patent because of the unique way we have decided to put the magnets into our design so that the magnets are secure.

The second patent classification that our team needs to have is Class 128, Subclass 200.19. This class is about surgery, which is important to our patent since our design will be eventually put into the human body. The subclass of this classification is for selectively dispensing fluid into the. This subclass is important in our classification because the goal of our swimmer is to deliver drugs throughout the body and target these drugs to the exact place that they need to go.

The third classification that our team will need to make for our patent is Class 441, Subclass 4. This class is concerning buoys, rafts, and aquatic devices. This classification is important to our patent because our swimmer is supposed to be able to swim in a viscous fluid. The subclass is concerning liquid cargo transfer. This is important for our swimmer because the swimmer will be holding the drug that will be sent to a specific spot in the body.

8.4 Review of Relevant Patents

Mechanical Fish Robot Exploiting Vibration Modes for Locomotion

This patent introduced the concept of using dominant nodes of vibration for locomotion by mimicking the movements of a living animal. The system consisted of one actuator to trigger the compliant part to vibrate, and additional actuators can be used to determine the driving direction. The prototype aimed to replicate movements of fish and was ⅓ the size of a real fish. Radio control was used to send signals to dictate the movement of the robot. The entire swimmer is encased by one flexible piece which keeps it sealed off from the water. This is different from our waterproofing method because we have moving parts outside of the waterproof casing. Our low Reynolds swimmer is similar in the sense that we are trying to examine the movements of bacteria to allow for movement in a highly viscous environment. Furthermore, our swimmer has an actuator motor to drive the frequency of the tail. Unlike the patent, our swimmer is a macroscopic model of the observed creature.

A Multi-Joint Underwater Robot Having a Complex Movement Function

This patent is about a multi joint underwater swimmer. The waterproofing method used for their moving parts is an oil filled type O-ring and the insulating oil acts as a barrier preventing the water from entering the system. This swimmer is similar to ours because it has moving pieces outside of the main body. However, their method for water proofing is different. The external pieces of our swimmer are not directly connected to the internal body like the swimmer from this patent is.

Microfluidic Apparatus and Methods for Performing Blood Typing and Crossmatching

Microfluidic cartridges designed for low Reynold's environments are presented in this patent. This design has reaction channels for antigen and antibody contents, which are layered in order to allow unmixed, HLFD (horizontally stratified laminar fluid diffusion). This device also potentiates the detection of antibody mediated agglutination at stratified areas. The main purpose of this device revolves around blood typing, cross-matching for blood transfusion, and immunodiagnostic agglutination assays. Similarly, our swimmer is motivated by the low Reynolds environment and usability in this viscous environment. Additionally, the applications are similar in the sense that this microswimmer will deliver drugs, treat different areas of the body, and allow for analysis in the various parts of the body.

Heart Assist Device with Expandable Impeller Pump

An impeller is shown in this patent. Impeller involves a configuration with a flexible drive shaft to drive the system. This prototype is primarily aimed to be used as a heart assist device with an expandable impeller pump. This pump is useful in pumping fluids including blood. The main similarity between our swimmer and this product is that it is applicable for being used in the human body and is microscopic. The difference, however, is that this patent is not supportive of a self-driving swimmer, whereas our microswimmer is self-driven.

Mass Production and Size Control of Nanoparticles through Controlled Micro Vortices

This patent mainly provides a description of mass production and size control of nanoparticles. Although it is not necessarily a product, the idea for creating microscopic products is applicable to our design. The patent also describes methods of creating polymeric and non-polymeric products, as well as hybrid ones that contain elements of both of the aforementioned types of materials. Our swimmer utilizes these types of base materials, so it would be helpful in the production of mass-producing our swimmer for the potential future market.

Method of making a biocompatible micro-swimmer, micro-swimmer and method of using such a micro-swimmer

This patent introduces the idea of using a biocompatible micro-swimmer and has significant potential to be used in the biomedical industry. Since this patent focuses on the swimmers potential uses in biomedicine, they have three objectives that will make the swimmer more fit for this future use. First, they want to make the swimmer naturally biodegradable such that no toxins are released inside the body. Then they want the swimmer to have a controlled active release of cargo for more precise drug delivery. The final objective is to make a swimmer that can maneuver through the body to a desired location without causing any excessive damage to the surrounding tissue. Although our project involves a macroscopic swimmer, the inspiration for our research was based on this idea of using micro swimmers in the body.

8.5 Conclusion

Based on the patent search our waterproofing design should be patentable because it was different from all the waterproofing methods, we found in our patent search. However, this is likely the only part of our design that we can patent because the patent search showed that there are lots of patents out for microswimmers and swimming in low Reynold's environments. This was expected because going into our project we knew that it was more about continuing research for swimming in a low Reynolds environment so there were not many new ideas or concepts. With that being said our waterproofing design with the internal and external magnets was an idea that we came up with and it fits the patent criteria.

Chapter 9: Engineering Standards

Dimensioning and Tolerancing ASME Y14.5

This engineering standard is established by the American Society of Mechanical Engineers and pertains to the comprehensive aspect of the design. The Y14.5 standard is relevant and integral to consider for our design because it allows for an organized description and understanding of the swimmer itself. By establishing the necessary symbols, requirements, and guidelines for the swimmer, other individuals can easily understand and utilize this system. Because the purpose of this microswimmer is to be integrated into and enhance the Healthcare system, having a detailed description of the dimensions can potentially expedite its marketability and globalization capability. With regards to its manufacturability, this standard proves effective from a financial perspective while improving quality and shortening deliveries. Important aspects of this standard contain critical information on CAD designs, degrees of freedom, datum references, composite position tolerances, symbology, and modifier tools.

Waterproofing Standard - ASTM C1127

This standard is important for our project because our swimmer contains components that can be damaged when coming into contact with a fluid. To make sure we met this standard we tested the outer casing of our swimmer by itself to make sure no liquid leaked in before putting the battery and motor in.

Health and Safety for Biomedical - ISO 13485

Although scaling down our swimmer to the nanoscale is out of the scope of our project, one of the potential uses of a nano swimmer is in the biomedical industry. This means it will likely be used inside the body, and therefore must be made from a biocompatible material.

Chapter 10: Environmental & Societal Impact

Our project was looking at the propulsion generated by an elastic tail in a low Reynolds environment. We used a macroscopic swimmer to analyze the propulsion in order to learn more about propulsive methods on the microscale.

The main assumptions pertaining to our project primarily revolve around our capabilities for completing our project. Knowing that we do not have the resources to create a swimmer at the micro scale, we chose to pursue a macroscopic model of the swimmer. Additionally, we have to take into consideration that the purpose of this project is mainly for biomedical advancement and application, so this project must abide by various health and safety standards. We also assumed that the environment of the swimmer is a very viscous, low Reynold's domain so we needed to research a method to find an effective propulsion method for the swimmer.

10.1 Environmental Impact

In the future, the swimmer will most likely be single use (a swimmer used in one person's body should not be reused in another), in order to maintain a sanitary treatment environment. This generates waste, and it is important to understand the environmental impact of this and try to curb it as much as possible. Something that can be looked into to reduce waste is biocompatible materials that are also biodegradable. This would mean that the swimmer is safe to use in the body but can also be discarded in a more environmentally conscious way.

To help combat the waste of our single use swimmer, it would be beneficial to come up with a way for it to be used multiple times. Since it will be used in the bodies of people that have cancer or other harmful cells in their body, it will be important that these swimmers are cleaned thoroughly. According to The Association of Medical Device Reprocessors, "over 15 million pounds of medical waste were diverted from landfills in 2019 thanks to the use of reprocessed single-use medical devices" (Weiss, E). This works by the hospital sending their medical devices that are usually used as single use to reprocessing centers. There, the reprocessing centers collect, sort, clean, and distribute the devices back to the hospitals so that they can be used again. However, we would need to make sure that this could be done on a micro-scale level, which may be too challenging.

If we are not able to clean the swimmers, then we will have to make them biodegradable in the body. Biodegradable medical equipment has been becoming more and more popular because, "Hospital-acquired infections (HAI) present major challenges to the healthcare industry with CDC estimation of 1 in 25 patients suffering from HAIs" (TMR Research). This means that we will want to make sure that our swimmer is biodegradable so that it can be a one-use device. However, this means that we will need to make sure that the materials of the swimmer will not be harmful to the body. Researchers have already started to create some biodegradable materials that are not harmful to the body. For example, there was a study done of the "production of magnetic materials with good biocompatibility and biodegradability" (Iafisco, M.) that proved a new chemical compound could be made on the micro-scale to be magnetic but also biodegradable. By having a biodegradable magnet that we could use in our swimmer, this is the big step we need to be able to have a fully biodegradable swimmer.

10.2 Societal Impact

The societal impact of medical devices is quite vast. According to the CDC, each year "about 650,000 cancer patients receive chemotherapy in an outpatient oncology clinic in the United States." As we have previously discussed, chemotherapy is quite a drastic procedure, attacking both healthy cells and cancer cells in order to fight the cancer. If our swimmer were used to treat those with cancer (by delivering drugs specifically to cancerous areas in the body), many, if not all of those 650,000 patients would not have to undergo chemotherapy in order to treat their cancer.

Another potential application of the swimmer is to clear blood clots in the body. When looking at statistics for the two most common blood clot conditions, deep vein thrombosis (DVT) and pulmonary embolism (PE), the CDC estimates that "as many as 900,000 people could be affected (1 to 2 per 1,000) each year in the United States", with about 60,000-100,000 of those patients dying from DVT/PE. Similarly, to cancer patients, DVT/PE patients would benefit greatly from a swimmer device that could clear these blot clots.

Both for cancer and blood clots, the use of swimmers as medical devices would be a great advance in the medical field. However, before all of these people can be helped, the swimmer needs to go through much testing and many clinical trials in order to be deemed safe. Our group wanted to look at the impact of the testing of medical devices, and how clinical trials can be done in the most ethical way possible. This encompasses who the device is tested on, how the tests are conducted, and how the information is shared. If the swimmers are tested ethically, then the societal impact of the swimmers will be of net benefit to the population.

One important aspect of the testing of our swimmer is to have a specific research question we are trying to answer with the clinical trials. That way the results of the tests are quantifiable and their purpose is easily understood. Another important consideration is that of a risk-benefit ratio, and making sure that the swimmer is developed enough before clinical trials that the benefit of testing the swimmer (the knowledge we will gain of how it works) is greater than the risk of actually putting the swimmer inside a patient's body. If the swimmer is not developed enough when clinical trials begin, the risk of using it on an actual patient widely outweighs the benefits that can be acquired from testing it, and this would not be ethical.

Another crucial part of clinical testing that will have to be detailed is the informed consent of the patients who are receiving treatment during the clinical trial. For there to be informed consent, it must be ensured that the patients "(1) are accurately informed of the purpose, methods, risks, benefits, and alternatives to the research, (2) understand this information and how it relates to their own clinical situation or interests, and (3) make a voluntary decision about whether to participate" (U.S. Department of Health and Human Services).

Lastly, we should also look at how the information from the clinical trials is shared. The patients who are involved in the trials should have their privacy respected. This is done mainly by keeping patients' private information confidential when the results are shared.

Overall, the scope of the project pertains to microswimmers and methods of propulsion at low Reynolds numbers. Because these swimmers will most likely be single use for sanitary measures, we researched potentially implementing biodegradability into our swimmer for the sake of sustainability. In regards to societal impacts, there are many applications that this swimmer encompasses. At the foundation is noninvasive treatment methods, and this leads to benefits for surgical treatments and clinical analysis.

Chapter 11: Summary & Conclusion

This paper explores the concept of swimming motion in very viscous, low Reynold's environments. Although the idea is somewhat far-fetched, after much literature review, we were able to find and build off existing resources. We then moved forward to the conceptual design stage to brainstorm the most efficient propulsion method for our swimmer and computed several calculations pertaining to force and viscosity. Then, we created a prototype for the swimmer by fabricating via Solid works and 3-D printing it. We also bought a large tank and filled it with corn syrup to mimic a macroscopic representation of a low Reynolds environment. We measured various results by altering the tail length and frequency of the motor. After the physical testing stage, we executed simulations through COMSOL by rotating the fluid around the tail filament and ran several tests with varying frequencies after defining the most optimal mesh. This project overall serves to be a steppingstone for future development of this swimmer in hopes of it being integrated into the medical industry for the growing demand of noninvasive treatment methods.

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Appendix A: Calculations & MATLAB Code

Below are the calculations for the pi groups used to set system requirements.

PI THEOREM:

1. List all variables
2. List the dimensions of all variables → MLTθ / → FLTθ
3. Determine number of different dimensions
4. Choose "NDD" number of repeating variables
   - → cannot form dimensionless group among themselves
   - → Don't choose the output of repeating variable.
5. Form π groups for the remaining variables
6. Form the dimensionless relation

(1) List all variables:

ρ, ℓ, μ, v, A, b, Ω

- v → output
- A → flexural rigidity
- b → distance from center

(2) List dimensions of all variables: F, L, T, θ

$\rho = FL^{-4}T^{2}$

$\ell = L$

$\mu = FL^{-2}T$

$v = LT^{-1}$

$\Omega = T^{-1}$

$b = L$

$A = FL^{2}$ → $E \cdot I$

$\frac{N}{m^2} = \frac{F}{L^2} \cdot L^4 = \frac{FL^4}{L^2} = FL^2$

③ Determine NDD

F, L, T = 3

NDD = 3

④ Choose NDD # of repeating variables

$\underbrace{\text{NDD \#}}_{3}$

$\ell = [L]$

$\Omega = [T^{-1}]$

$\mu = [F L^{-2} T]$

⑤ Form Π groups from repeating variables for remaing variables

Π ↓ dimensionless

For v:

$\Pi_1 = v\, \ell^a \Omega^b \mu^c$

$(LT^{-1})(L)^a(T^{-1})^b(FL^{-2}T)^c$

L^{1+a-2c} $\quad 1+a=0 \quad a=-1$

T^{-1-b+c} $\quad -1-b=0 \quad b=-1$

F^c $\quad c=0$

$\Pi_1 = v\,\ell^{-1}\Omega^{-1}$

$\Pi_1 = \dfrac{v}{\ell\Omega}$

For ρ:

$$\pi_2 = \rho\, l^a \Omega^b \mu^c$$

$$(FL^{-4}T^2)(L)^a(T^{-1})^b(FL^{-2}T)^c$$

F^{1+c} $c=-1$

$L^{-4+a-2c}$ $-4+a+2=0$, $a=2$

T^{2-b+c} $2-b-1=0$, $-b+1=0$, $-b=-1$, $b=1$

$$\pi_2 = \rho l^2 \Omega^1 \mu^{-1} = \frac{\rho l^2 \Omega}{\mu}$$

For A:

$$\pi_3 = A\, l^a \Omega^b \mu^c$$

$$(FL^2)(L)^a(T^{-1})^b(FL^{-2}T)^c$$

F^{1+c} $c=-1$

L^{2+a-2c} $2+a+2=0$, $a=-4$

T^{-1b+c} $-b-1=0$, $-b=1$, $b=-1$

$$A \cdot l^{-4} \cdot \Omega^{-1} \cdot \mu^{-1}$$

$$\pi_3 = \frac{A}{l^4 \Omega \mu}$$

⑥ Form a dimensionless relation

$$\pi_1 = f(\pi_2, \pi_3)$$

$$\frac{V}{l\Omega} = \left(\frac{\rho l^2 \Omega}{\mu}, \frac{A}{l^4 \Omega \mu}\right)$$

Below are the calculations for finding the neutral buoyancy of the swimmer

$$F_b = \rho V g$$

↳ want to equal $F_{swim} = m_s g$

$$\rho V \cancel{g} = m_s \cancel{g}$$

$$\rho V = m_s$$

↳ m fluid displaced

for V:

Assuming swimmer is a cylinder (body)

$$V = \pi r^2 h = \pi \left(\frac{0.035}{2} \right)^2 \cdot 0.073 = 7.023 \times 10^{-5} \, m^3$$

↳ this is smaller than actual volume, so final mass will be smaller than needed

for water:

$$m_{fd} = m_s$$

$$m_{fd} = \rho V = 1000 \frac{kg}{m^3} \cdot (7.023 \times 10^{-5}) m^3 = 0.0702 \, kg = 70 \, g$$

for corn syrup:

$$m_{fd} = m_s$$

$$m_{fd} = \rho V = 1400 \frac{kg}{m^3} \cdot (7.023 \times 10^{-5}) \, m^3 = 0.0983 \, kg = 98 \, g$$

Below is the Arduino code used to remotely actuate the swimmer for testing:

```
#include <SPI.h>
#include <WiFiNINA.h>

#include "arduino_secrets.h"
///////please enter your sensitive data in the Secret tab/arduino_secrets.h
char ssid[] = SECRET_SSID;        // your network SSID (name)
char pass[] = SECRET_PASS;    // your network password (use for WPA, or use as key for
WEP)
int keyIndex = 0;                 // your network key index number (needed only for WEP)

int status = WL_IDLE_STATUS;
WiFiServer server(80);
#define PWMpin 10

void setup() {
  Serial.begin(9600);      // initialize serial communication
  pinMode(PWMpin,OUTPUT);

  // check for the WiFi module:
  if (WiFi.status() == WL_NO_MODULE) {
    Serial.println("Communication with WiFi module failed!");
    // don't continue
    while (true);
  }

  String fv = WiFi.firmwareVersion();
  if (fv < WIFI_FIRMWARE_LATEST_VERSION) {
    Serial.println("Please upgrade the firmware");
  }


  while (status != WL_CONNECTED) {
    Serial.print("Attempting to connect to Network named: ");
    Serial.println(ssid);                   // print the network name (SSID);


    status = WiFi.begin(ssid, pass);

    delay(10000);
  }
  server.begin();
  printWifiStatus();
}

void loop() {
  WiFiClient client = server.available();
```

```
 if (client) {                          // this is to print on serial monitor if there is a connection ("client")
   Serial.println("new client");
   String currentLine = "";
   while (client.connected()) {
     if (client.available()) {
       char c = client.read();
       Serial.write(c);
       if (c == '\n') {


         if (currentLine.length() == 0) {
           client.println("HTTP/1.1 200 OK");
           client.println("Content-type:text/html");
           client.println();
           client.println("<body style=background-color:dodgerblue>");
          client.println("<font style='color:white'>");
          client.println("<font style='font-family:verdana'>");

           // page content
           client.print("<center> <h1> <font color='white'> Low Re Swimmer Remote
Control</font> </h1> </center>");

           client.println("<a href=\"/H\"\"><button style='font-size:150%;background-
color:SpringGreen; color:black; border-radius:50px; position:absolute; top:100px;
left:550px'>Turn Motor On (Max Speed)</button></a>");
           client.println("<a href=\"/A\"\"><button style='font-size:120%;background-
color:LightSkyBlue; color:black; border-radius:50px; position:absolute; top:200px;
left:150px'>Motor Speed 1 </button></a>");
           client.println("<a href=\"/B\"\"><button style='font-size:120%;background-
color:LightSkyBlue; color:black; border-radius:50px; position:absolute; top:200px;
left:350px'>Motor Speed 2 </button></a>");
           client.println("<a href=\"/C\"\"><button style='font-size:120%;background-
color:LightSkyBlue; color:black; border-radius:50px; position:absolute; top:200px;
left:550px'>Motor Speed 3 </button></a>");
           client.println("<a href=\"/D\"\"><button style='font-size:120%;background-
color:LightSkyBlue; color:black; border-radius:50px; position:absolute; top:200px;
left:750px'>Motor Speed 4 </button></a>");
           client.println("<a href=\"/E\"\"><button style='font-size:120%;background-
color:LightSkyBlue; color:black; border-radius:50px; position:absolute; top:200px;
left:950px'>Motor Speed 5 </button></a>");
           client.println("<a href=\"/F\"\"><button style='font-size:120%;background-
color:LightSkyBlue; color:black; border-radius:50px; position:absolute; top:300px;
left:150px'>Motor Speed 6 </button></a>");
           client.println("<a href=\"/G\"\"><button style='font-size:120%;background-
color:LightSkyBlue; color:black; border-radius:50px; position:absolute; top:300px;
left:350px'>Motor Speed 7 </button></a>");
```

```
          client.println("<a href=\"/I\"\"><button style='font-size:120%;background-color:LightSkyBlue; color:black; border-radius:50px; position:absolute; top:300px; left:550px'>Motor Speed 8 </button></a>");
          client.println("<a href=\"/J\"\"><button style='font-size:120%;background-color:LightSkyBlue; color:black; border-radius:50px; position:absolute; top:300px; left:750px'>Motor Speed 9 </button></a>");
          client.println("<a href=\"/K\"\"><button style='font-size:120%;background-color:LightSkyBlue; color:black; border-radius:50px; position:absolute; top:300px; left:950px'>Motor Speed 10 </button></a>");
          client.println("<a href=\"/L\"\"><button style='font-size:150%;background-color:Tomato; color:black; border-radius:50px; position:absolute; top:400px; left:600px'> Turn Motor Off </button></a>");

          // The HTTP response ends with another blank line:
          client.println();
          // break out of the while loop:
          break;
        } else {    // if you got a newline, then clear currentLine:
          currentLine = "";
        }
      } else if (c != '\r') {  // if you got anything else but a carriage return character,
        currentLine += c;      // add it to the end of the currentLine
      }

      // Check to see if the client request was "GET /H" or "GET /L":
      if (currentLine.endsWith("GET /H")) {
        analogWrite(PWMpin,255);              // GET /H turns the motor on
      }
      if (currentLine.endsWith("GET /L")) {
        analogWrite(PWMpin,0);                // GET /L turns the motor off
      }
      if (currentLine.endsWith("GET /A")) {
        analogWrite(PWMpin,50);               // GET /A turns the motor on at 10%
      }
      if (currentLine.endsWith("GET /B")) {
        analogWrite(PWMpin,70);               // GET /B turns the motor on at 20%
      }
      if (currentLine.endsWith("GET /C")) {
        analogWrite(PWMpin,90);               // GET /C turns the motor on at 30%
      }
      if (currentLine.endsWith("GET /D")) {
        analogWrite(PWMpin,110);              // GET /D turns the motor on at 40%
      }
      if (currentLine.endsWith("GET /E")) {
        analogWrite(PWMpin,130);              // GET /E turns the motor on at 50%
      }
      if (currentLine.endsWith("GET /F")) {
        analogWrite(PWMpin,150);              // GET /F turns the motor on at 60%
      }
```

```
        if (currentLine.endsWith("GET /G")) {
          analogWrite(PWMpin,170);              // GET /G turns the motor on at 70%
        }
        if (currentLine.endsWith("GET /I")) {
          analogWrite(PWMpin,190);              // GET /H turns the motor on at 80%
        }
        if (currentLine.endsWith("GET /J")) {
          analogWrite(PWMpin,210);              // GET /J turns the motor on at 90%
        }
        if (currentLine.endsWith("GET /K")) {
          analogWrite(PWMpin,230);              // GET /K turns the motor on at 100%
        }

      }
    }
    // close the connection:
    client.stop();
    Serial.println("client disconnected");
  }
}

void printWifiStatus() {
  // print the SSID of the network you're attached to:
  Serial.print("SSID: ");
  Serial.println(WiFi.SSID());

  // print your board's IP address:
  IPAddress ip = WiFi.localIP();
  Serial.print("IP Address: ");
  Serial.println(ip);

  // print the received signal strength:
  long rssi = WiFi.RSSI();
  Serial.print("signal strength (RSSI):");
  Serial.print(rssi);
  Serial.println(" dBm");
  // print where to go in a browser:
  Serial.print("To see this page in action, open a browser to http://");
  Serial.println(ip);
}
```

Appendix B: Assembly Drawings

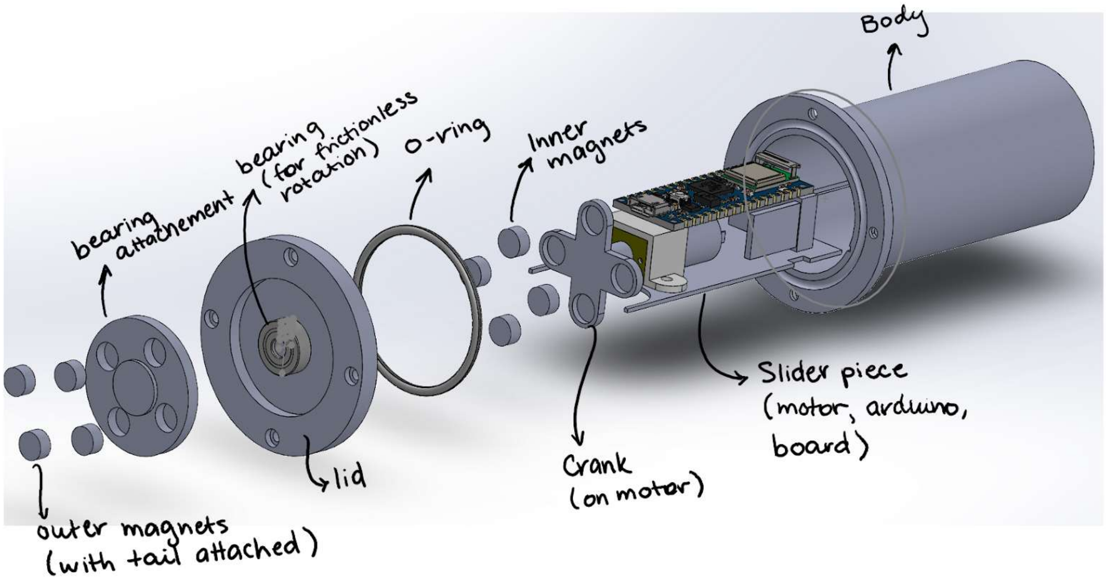


Figure B.1: Exploded view of 3D swimmer

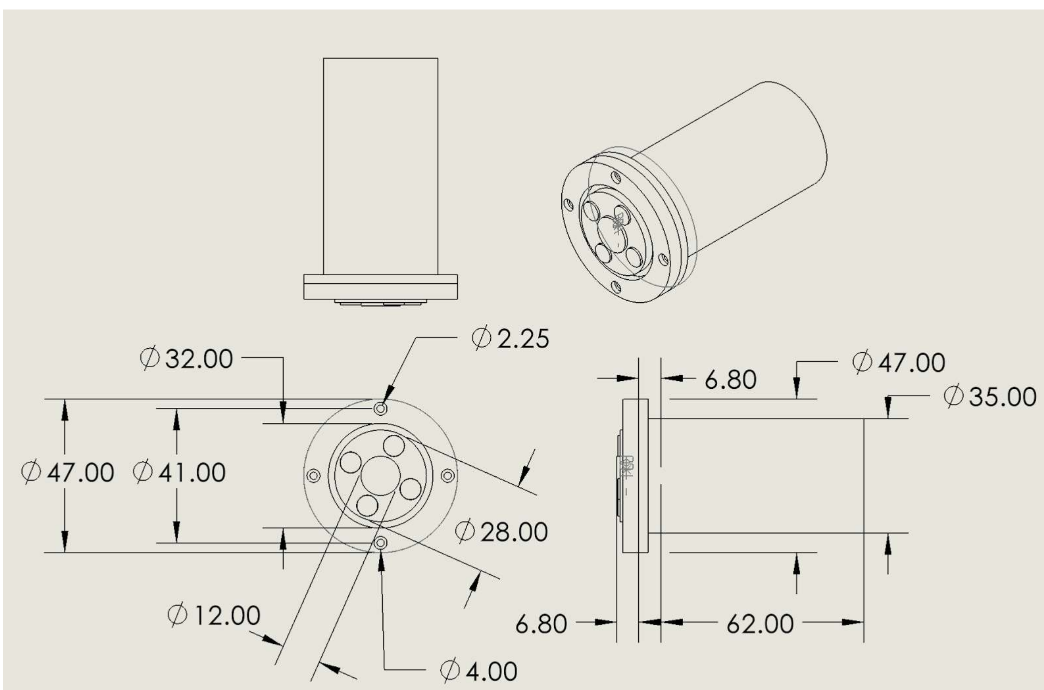


Figure B.2: Detail drawing of 3D swimmer

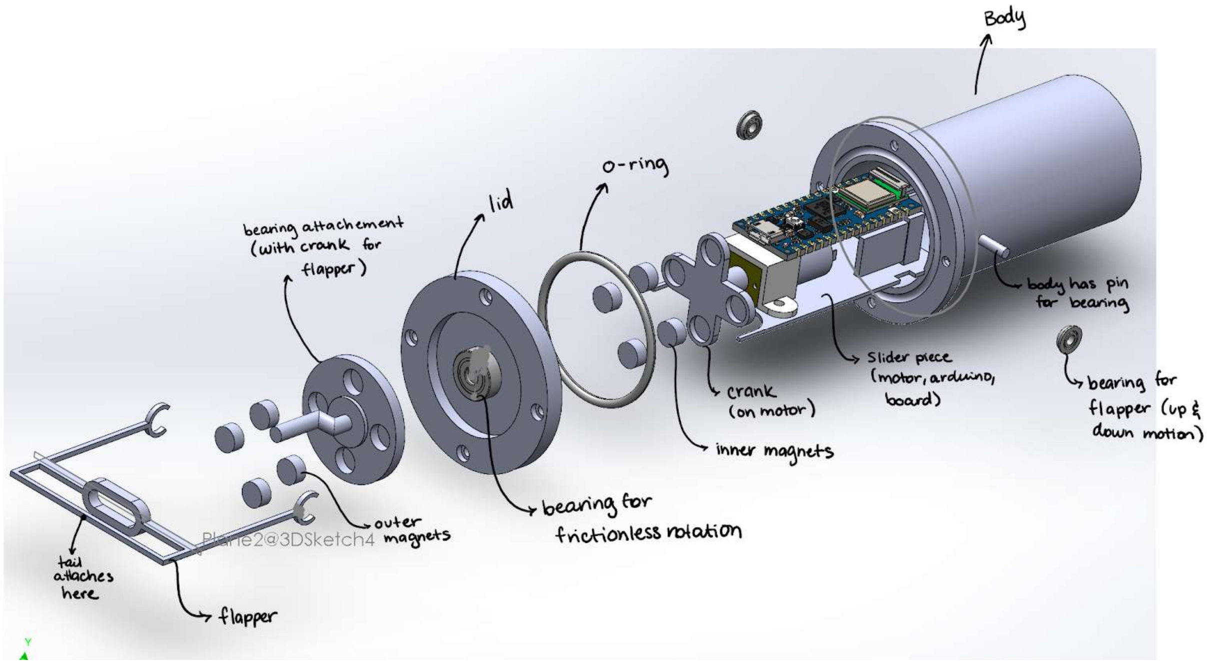


Figure B.3: Exploded view of 2D swimmer

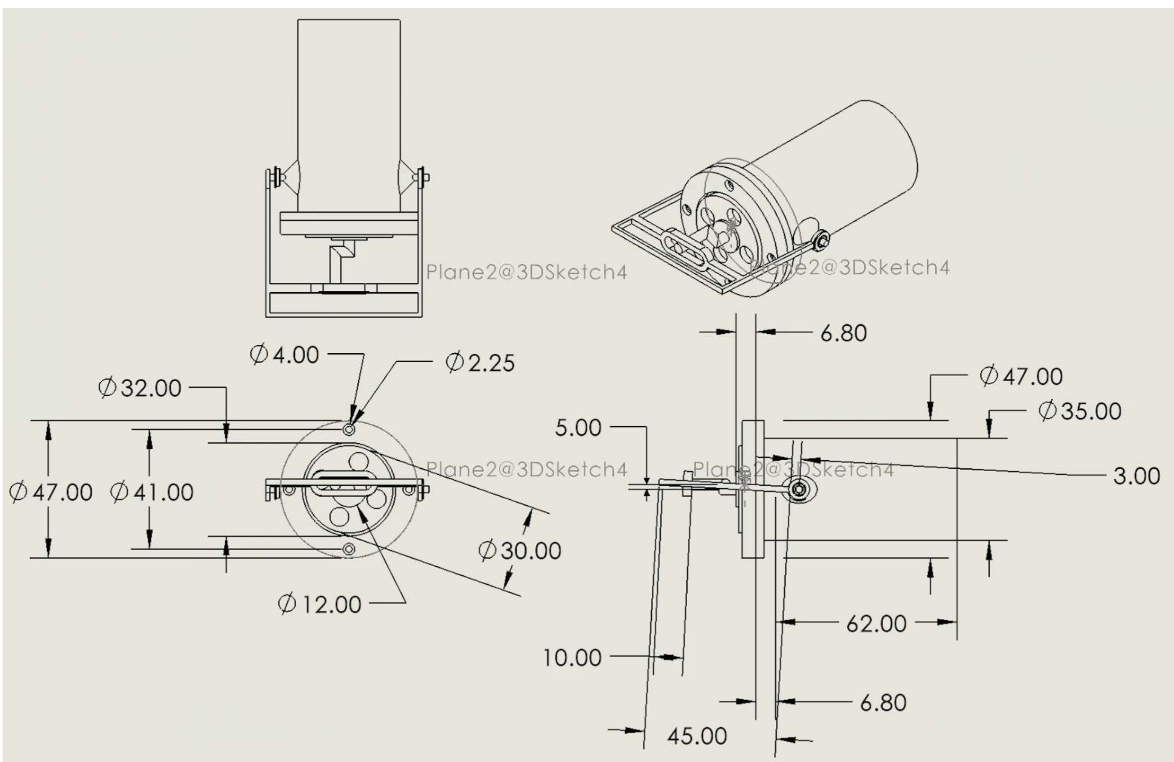


Figure B.4: Detail drawing of 2D swimmer

Appendix C: PDS Requirements

Table C.1: PDS Requirements

REQUIREMENTS	UNITS	DATUM	TARGET RANGE
Performance			
Low Reynolds number fluid			10^{-2}-10^{-3}
Tail rotation rate	Hz	1	.5-2
Velocity of swimmer	mm/s		
Size			
Head length	cm	3.5	3-8
Head diameter	cm	2	2.5-1.5
Tail length	cm	6	6-25
Other			
Waterproof			
Controlled oscillation rate			

Appendix D: QFD Information

Table D.1: Customer Needs

	Priority Level		
Customer Needs	**I**	**II**	**III**
Low cost		II	
Capable of swimming in low Reynolds environment			III
Can be scaled down			III
Non-tethered swimmer			III
Integrated sensory/imaging		II	
Ability to control direction		II	
Ability to control velocity	I		
Materials are biocompatible	I		
Can be mass manufactured	I		

Appendix E: Decision Matrix

Table E.1: Decision Matrix

<table>
<tr><th colspan="6">Propulsion Subsystem</th></tr>
<tr><td></td><td>Importance</td><td>Guitar string</td><td>Flexible sheet</td><td>Rotational</td><td>Linear</td></tr>
<tr><td>Satisfies SP number</td><td>4</td><td>4</td><td>2</td><td>4</td><td>3</td></tr>
<tr><td>Able to simulate</td><td>2</td><td>3</td><td>2</td><td>2</td><td>4</td></tr>
<tr><td>Cost</td><td>1</td><td>4</td><td>4</td><td>4</td><td>3</td></tr>
<tr><td>Manufacturable</td><td>2</td><td>4</td><td>3</td><td>4</td><td>3</td></tr>
<tr><th colspan="6">Fluid Subsystem</th></tr>
<tr><td></td><td>Importance</td><td colspan="2">Silicon oil</td><td colspan="2">Corn Syrup</td></tr>
<tr><td>High viscosity</td><td>4</td><td colspan="2">4</td><td colspan="2">3</td></tr>
<tr><td>Visibility</td><td>3</td><td colspan="2">4</td><td colspan="2">4</td></tr>
<tr><td>Cost</td><td>2</td><td colspan="2">2</td><td colspan="2">4</td></tr>
<tr><td>safety</td><td>3</td><td colspan="2">2</td><td colspan="2">3</td></tr>
<tr><th colspan="6">Measurement Subsystem</th></tr>
<tr><td></td><td>Importance</td><td colspan="2">Camera/tape measure (speed)</td><td colspan="2">Cantilever beam (propulsion)</td></tr>
<tr><td>Characterize performance</td><td>4</td><td colspan="2">4</td><td colspan="2">3</td></tr>
<tr><td>Accuracy</td><td>4</td><td colspan="2">4</td><td colspan="2">3</td></tr>
<tr><td>Cost</td><td>2</td><td colspan="2">4</td><td colspan="2">2</td></tr>
</table>

Appendix F: Timeline

Table F.1: Senior Design Team Timeline

WEEK	CLASS ASSIGNMENTS	PROJECT TASKS
FALL		
1	Set up design team and project	
2	Project Proposal	Set up team roles/dynamics
3	Preliminary Research and Product Review	
4	Problem Statement, Team	- Research similar projects - Start funding proposal - Brainstorm swimmer movement method
5	Preliminary CN Report	- Deepen understanding of concepts - pros/cons for swimmer ideas - funding proposal draft for Pak
6	PDS Oral and Written Report	- Final Funding proposal - Narrow down and further develop logistics of swimmer ideas
7	Final CN and info gathering report	- test feasibility of magnet idea
8	10+ ideas selection matrices	- start theoretical calculations
9	Product testing, updated customer data	- focus on one design
10	Draft CDR, Safety review	-start drawings and CAD designs
11	Conceptual Design Report, mock up	

WINTER	
Beginning	Detailed drawings and preliminary testing
Middle	Simulation (FEA) and CAD modeling
End	Begin constructing physical prototypes and testing
SPRING	

Beginning	Performance testing
Middle	Senior design conference
End	Open house

Appendix G: Budget

Table G.1: Funding Requested

Item	Cost Per Units ($)	Amount	Cost ($)
Silicone Oil	1000	1	1000
Robotics Components	600	1	600
Hydraulic and Pneumatic Components	400	1	400
		Total:	2000

Table G.2: Bill of Materials for Swimmer Prototype

Category	Item	Purpose	Quantity	Unit Cost	Total Cost
Propulsion system	guitar string	to be used as the tail of the swimmer	1	$5.49	$5.49
Propulsion system	dc motor	used to power the swimmer	1	$13.99	$13.99
Propulsion system	battery connectors	used to connect the batteries to the wired assembly	2	$0.17	$0.34
Propulsion system	battery charger	used to recharge the swimmer batteries between tests	1	$6.95	$6.95
Propulsion system	battery	used to power the swimmer	2	$5.95	$11.90
Propulsion system	protoboard	used as a base for the swimmer wiring	1	$1.75	$1.75

Control system	Arduino Nano 33 IOT	used as the swimmers microcontroller	1	$16.95	$16.95
Assembly	Tungsten Putty	used to add weight to the swimmer to make it neutrally buoyant	2	$8.95	$17.90
Testing equipment	Tape Measure	placed behind the swimmer tank to take experimental data	1	$3.99	$3.99
Fluid system	Corn Syrup	swimmer testing fluid	8	$37.49	$299.92
Testing equipment	Fishing Line	used as a guide rail for the swimmer to keep it in a straight trajectory	1	$7.88	$7.88
Testing equipment	Eye Pin Hooks (pack of 100)	hooks placed on body of swimmer to connect to fishing line guide rail	1	$4.99	$4.99
Assembly	Epoxy Putty	Used to make various connections in the swimmer assembly	1	$5.97	$5.97
Propulsion system	O-ring (pack of 50)	used to make a watertight seal between lid and body of swimmer	1	$10.29	$10.29
Propulsion system	Hex Nut (pack of 50)	Used for screwing lid to body	1	$1.59	$1.59
Propulsion system	Screws (pack of 5)	Used for screwing lid to body	1	$8.21	$8.21
Assembly	3D Printer PLA Filament	Used to 3D print parts of the swimmer, such as body and lid	1	$19.99	$19.99
Assembly	Lead Free Solder	used to solder the wiring of the swimmer	1	$5.43	$5.43
Fluid system	40 Gallon Fish tank	used to test the prototype	1	$79.99	$79.99

Appendix H: Experimental Data

Table H.1: Experimental Data for All Trials

Tail Length (mm)	Distance Traveled (mm)	Time (s)
25	20	126
25	20	95
25	20	127
45	20	76
45	20	70
45	20	61
65	20	62
65	20	60
65	20	67
85	20	54
85	20	53
85	20	49
105	20	37
105	20	44
105	20	39

Table H.2: Averaged experimental data with speed result

Tail Length (mm)	**Distance Traveled (mm)**	**Time (s)**	**Speed (mm/s)**
25	20	116	0.17
45	20	69	0.29
65	20	63	0.32
85	20	52	0.38
105	20	40	0.50

Appendix I: Patent Sketches

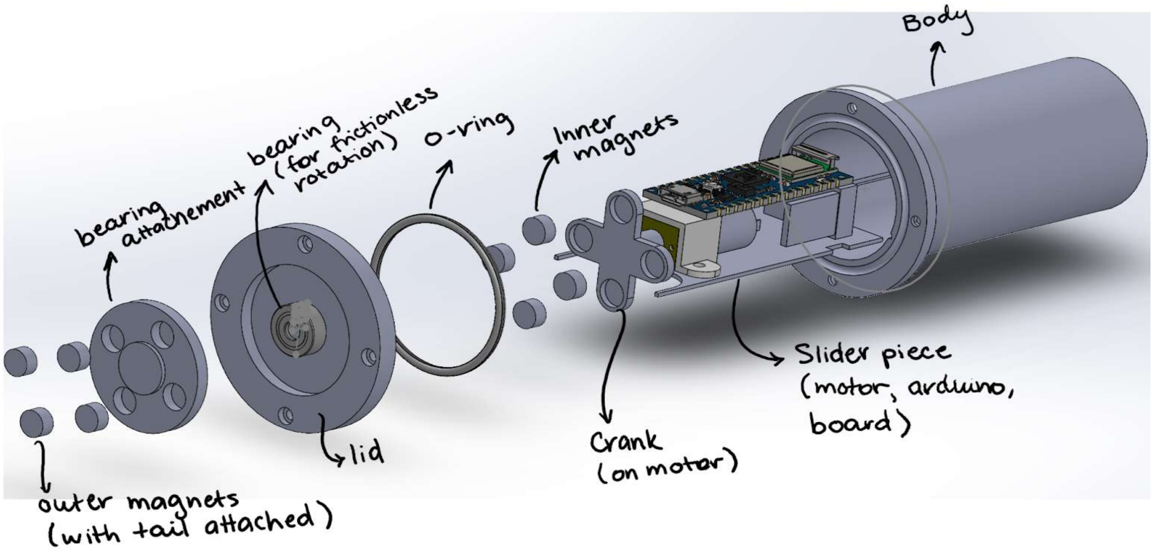


Figure I.1: Exploded view of macroscale microswimmer

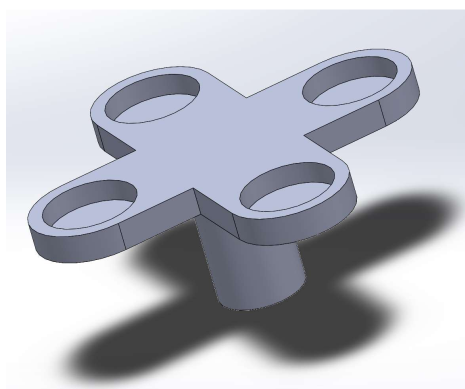


Figure I.2: 4 arm attachment for motor

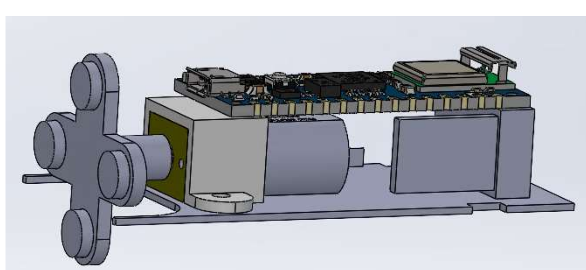


Figure I.3: 4 arm attachment for motor on motor

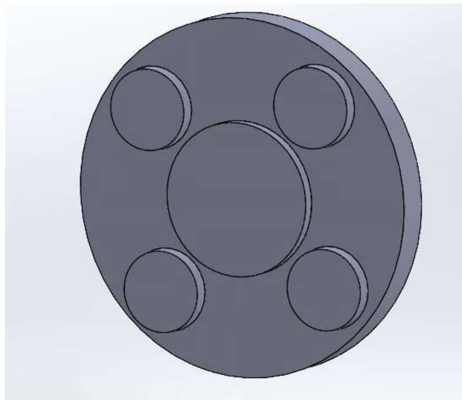


Figure I.4: Outside piece for tail attachment (tails can be attached to the 4 magnets shown)

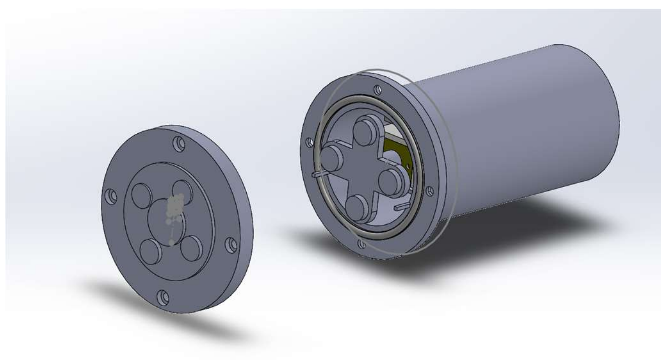


Figure I.5: Circular attachment on lid shown in relation to body of swimmer

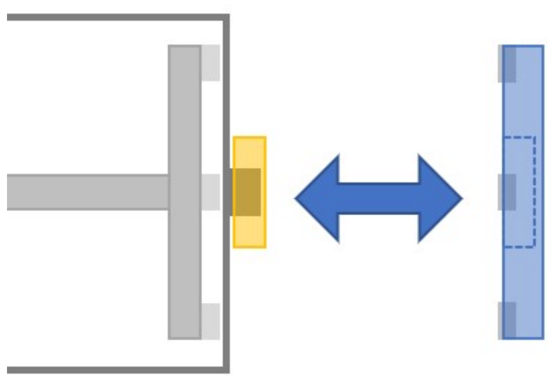
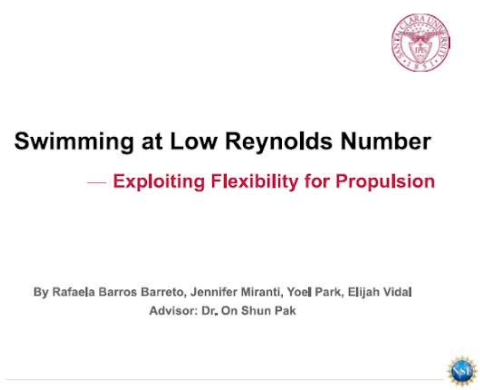
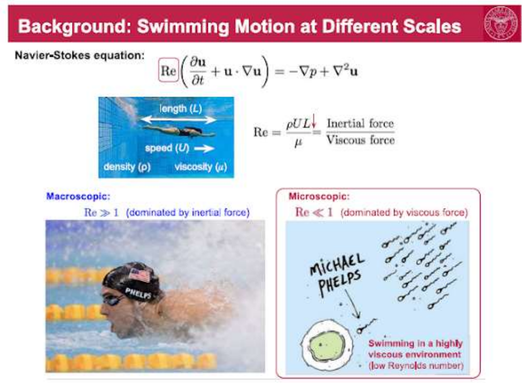
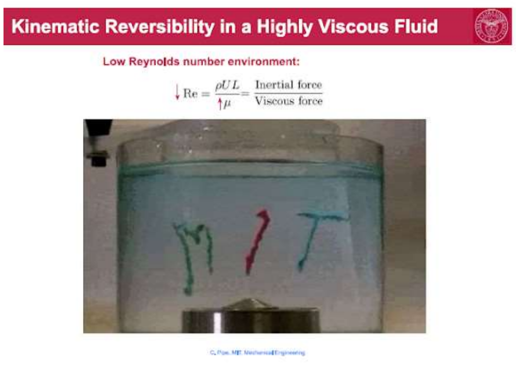


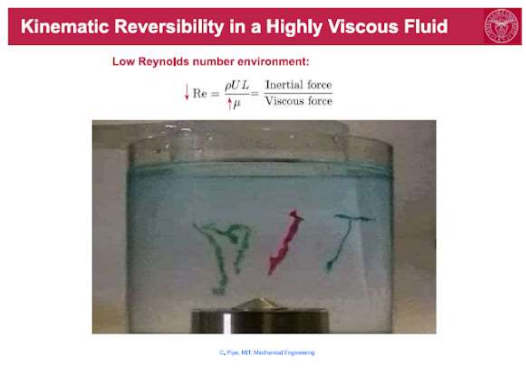
Figure I.6: Visual sketch of the magnets function

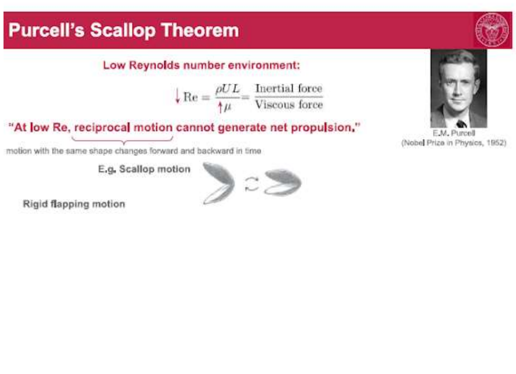
Appendix J: Conference Slides

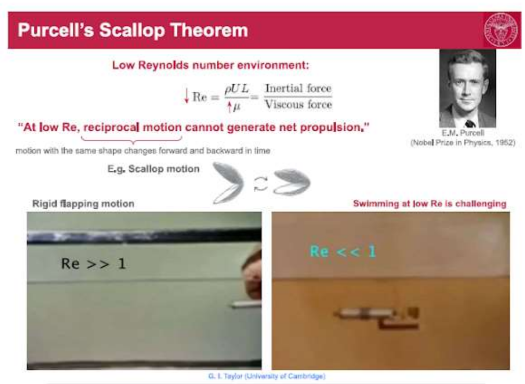


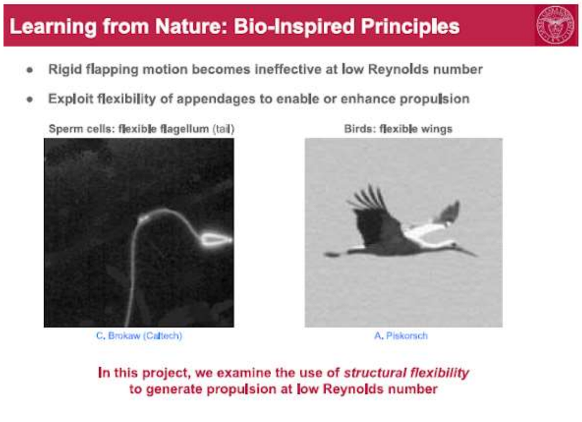


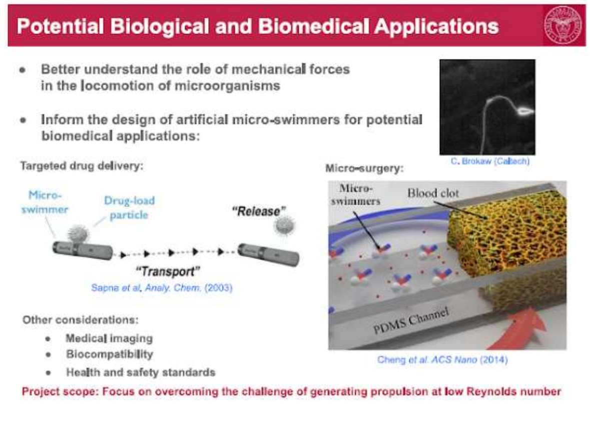




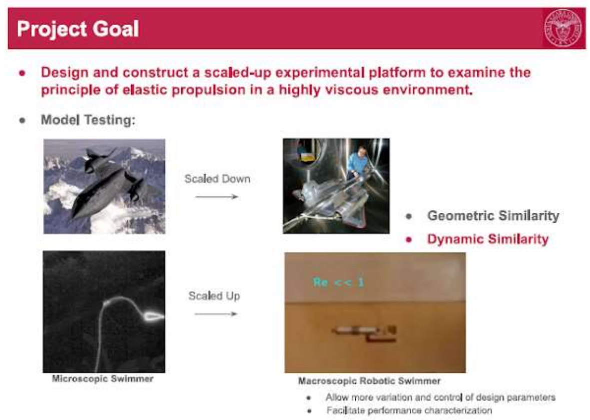


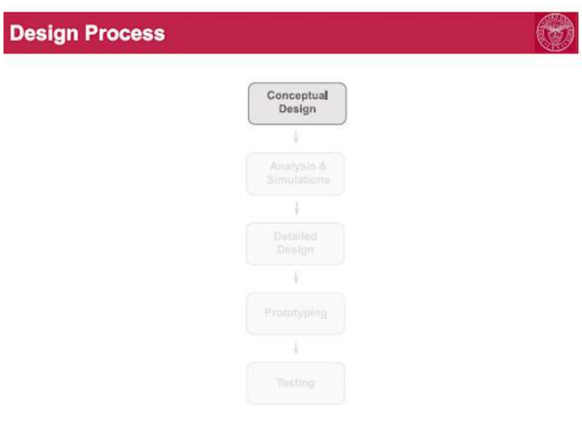


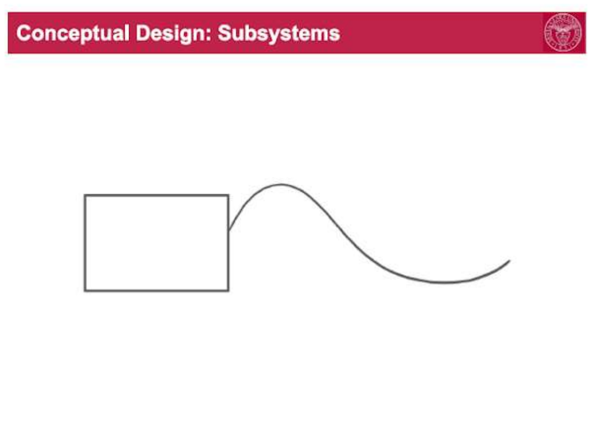

Learning from Nature: Bio-Inspired Principles
Rigid flapping motion becomes ineffective at low Reynolds number
Exploit flexibility of appendages to enable or enhance propulsion
Sperm cells: flexible flagellum (tail)
Birds: flexible wings
C. Brokaw (Caltech)
A. Piskorsch
In this project, we examine the use of structural flexibility
to generate propulsion at low Reynolds number

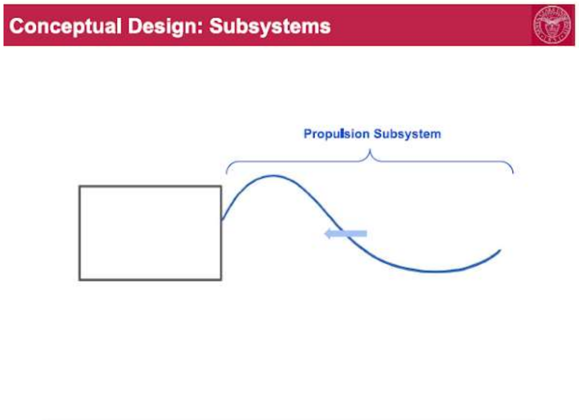

Potential Biological and Biomedical Applications
Better understand the role of mechanical forces in the locomotion of microorganisms
Inform the design of artificial micro-swimmers for potential biomedical applications:
C. Brokaw (Caltech)
Targeted drug delivery:
Micro-swimmer
Drug-load particle
"Release"
"Transport"
Sapne et al, Analy. Chem. (2003)
Micro-surgery:
Micro-swimmers
Blood clot
PDMS Channel
Cheng et al. ACS Nano (2014)
Other considerations:
Medical imaging
Biocompatibility
Health and safety standards
Project scope: Focus on overcoming the challenge of generating propulsion at low Reynolds number

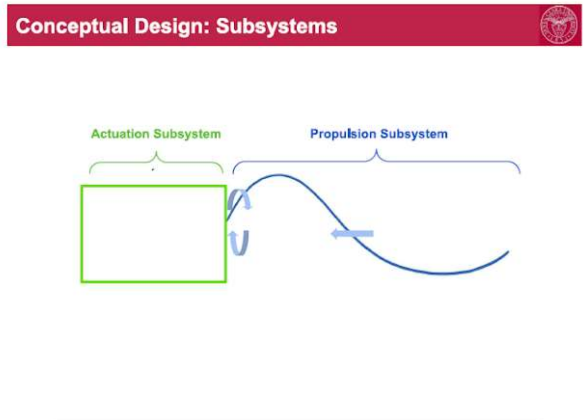

Project Goal
Design and construct a scaled-up experimental platform to examine the principle of elastic propulsion in a highly viscous environment.
Model Testing:
Scaled Down
Geometric Similarity
Dynamic Similarity
Scaled Up
Re << 1
Microscopic Swimmer
Macroscopic Robotic Swimmer
Allow more variation and control of design parameters
Facilitate performance characterization

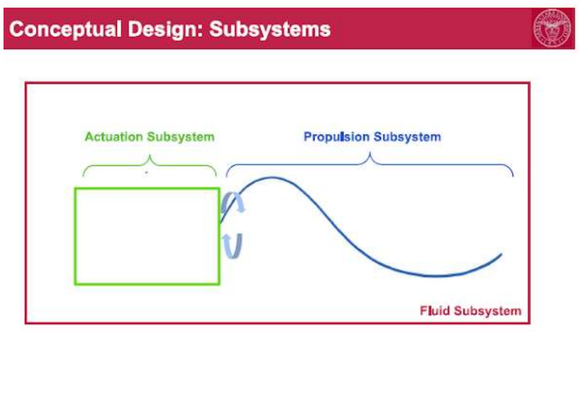

Project Goal
Design and construct a scaled-up experimental platform to examine the principle of elastic propulsion in a highly viscous environment.
Model Testing:
Scaled Down
Geometric Similarity
Dynamic Similarity
Scaled Up
Re << 1
Microscopic Swimmer
Macroscopic Robotic Swimmer
Allow more variation and control of design parameters
Facilitate performance characterization

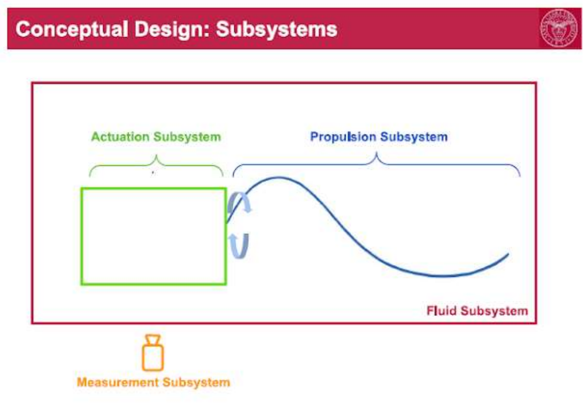

Design Process
Conceptual Design
Analysis & Simulations
Detailed Design
Prototyping
Testing

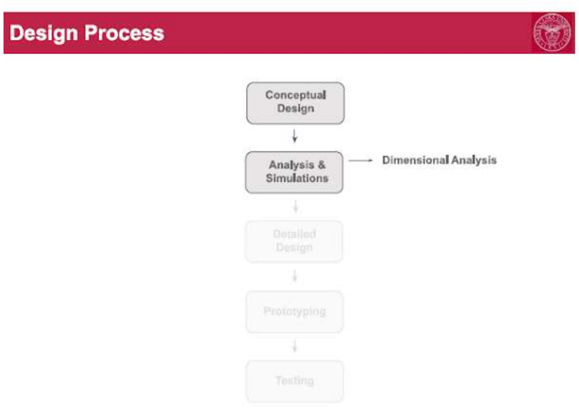

Conceptual Design: Subsystems

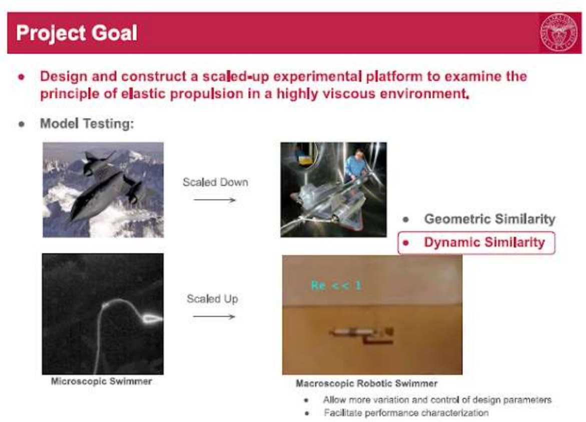

Conceptual Design: Subsystems
Propulsion Subsystem

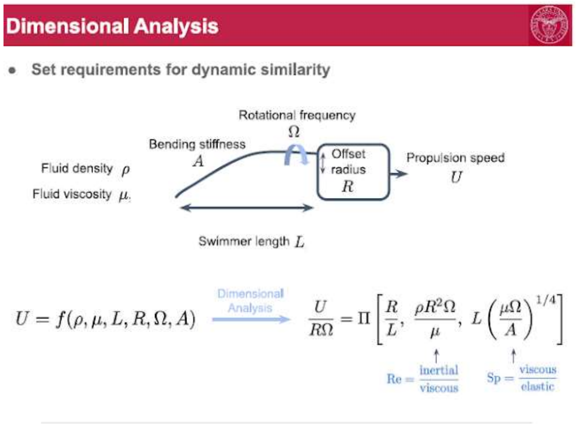

Conceptual Design: Subsystems
Actuation Subsystem
Propulsion Subsystem

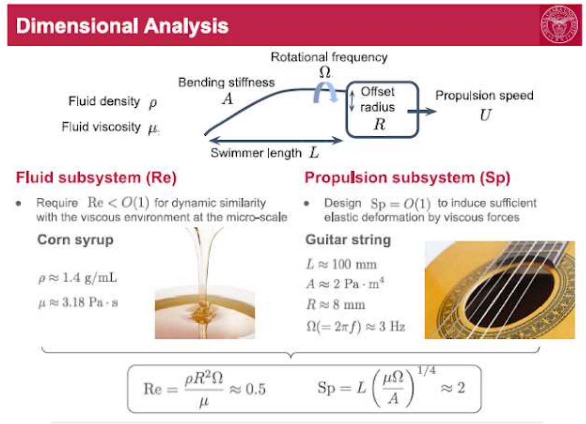

Conceptual Design: Subsystems
Actuation Subsystem
Propulsion Subsystem
Fluid Subsystem

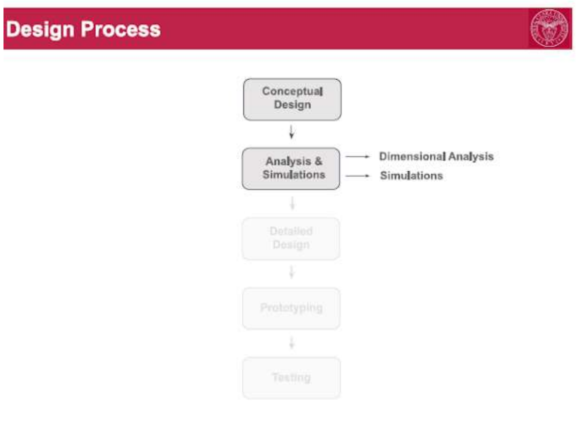

Conceptual Design: Subsystems
Actuation Subsystem
Propulsion Subsystem
Fluid Subsystem
Measurement Subsystem

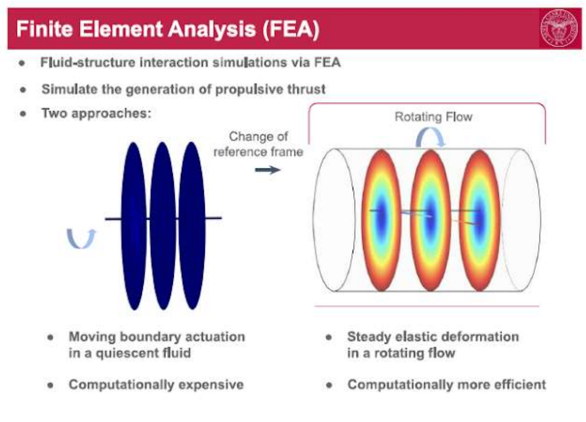

Design Process
Conceptual Design
Analysis & Simulations
Dimensional Analysis
Detailed Design
Prototyping
Testing

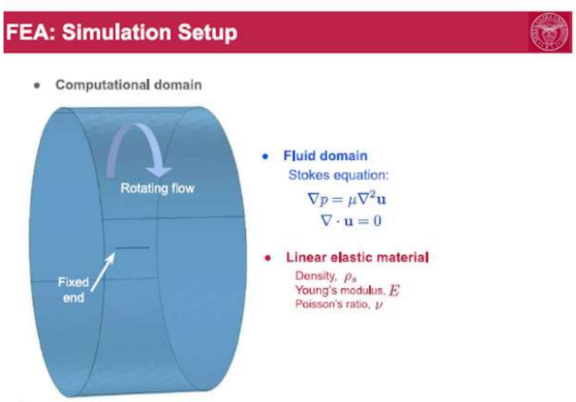

Project Goal
Design and construct a scaled-up experimental platform to examine the principle of elastic propulsion in a highly viscous environment.
Model Testing:
Scaled Down
Geometric Similarity
Dynamic Similarity
Scaled Up
Re << 1
Microscopic Swimmer
Macroscopic Robotic Swimmer
Allow more variation and control of design parameters
Facilitate performance characterization

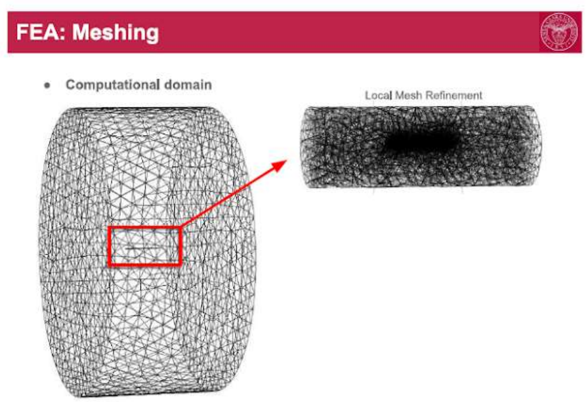

Dimensional Analysis
Set requirements for dynamic similarity
Rotational frequency Ω
Bending stiffness A
Fluid density ρ
Fluid viscosity μ
Offset radius R
Propulsion speed U
Swimmer length L
$U = f(\rho, \mu, L, R, \Omega, A)$
Dimensional Analysis
$\frac{U}{R\Omega} = \Pi\left[\frac{R}{L}, \frac{\rho R^2\Omega}{\mu}, L\left(\frac{\mu\Omega}{A}\right)^{1/4}\right]$
$\mathrm{Re} = \frac{\text{inertial}}{\text{viscous}}$
$\mathrm{Sp} = \frac{\text{viscous}}{\text{elastic}}$

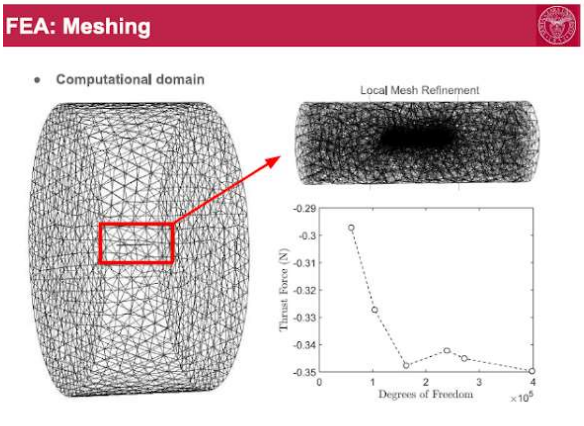

Dimensional Analysis
Rotational frequency Ω
Bending stiffness A
Fluid density ρ
Fluid viscosity μ
Offset radius R
Propulsion speed U
Swimmer length L
Fluid subsystem (Re)
Require $\mathrm{Re} < O(1)$ for dynamic similarity with the viscous environment at the micro-scale
Corn syrup
$\rho \approx 1.4$ g/mL
$\mu \approx 3.18$ Pa·s
Propulsion subsystem (Sp)
Design $\mathrm{Sp} = O(1)$ to induce sufficient elastic deformation by viscous forces
Guitar string
$L \approx 100$ mm
$A \approx 2$ Pa·m^4
$R \approx 8$ mm
$\Omega(= 2\pi f) \approx 3$ Hz
$\mathrm{Re} = \frac{\rho R^2 \Omega}{\mu} \approx 0.5$
$\mathrm{Sp} = L\left(\frac{\mu\Omega}{A}\right)^{1/4} \approx 2$

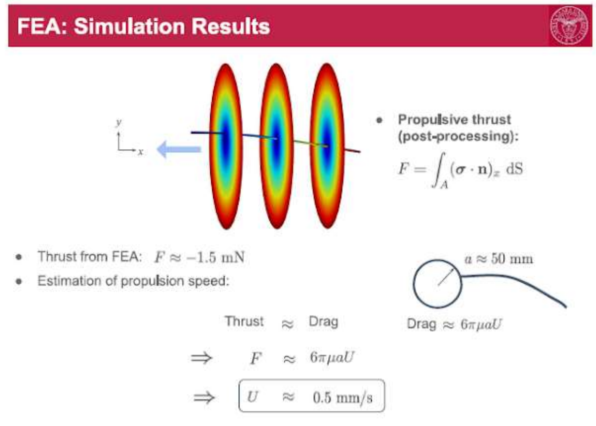

Design Process
Conceptual Design
Analysis & Simulations
Dimensional Analysis
Simulations
Detailed Design
Prototyping
Testing

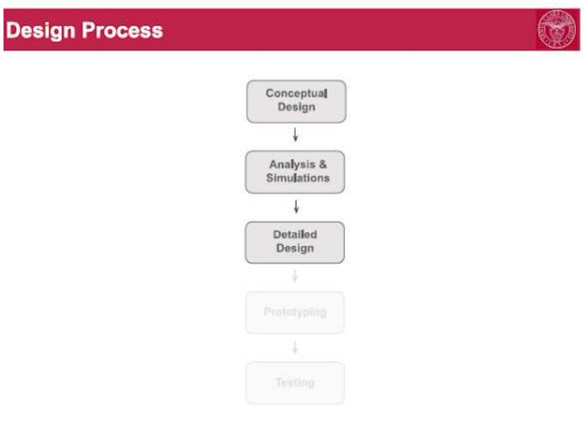

Finite Element Analysis (FEA)
Fluid-structure interaction simulations via FEA
Simulate the generation of propulsive thrust
Two approaches:
Change of reference frame
Rotating Flow
Moving boundary actuation in a quiescent fluid
Computationally expensive
Steady elastic deformation in a rotating flow
Computationally more efficient

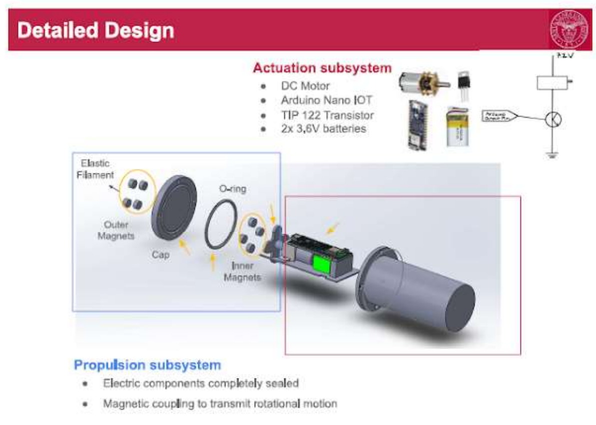

FEA: Simulation Setup
Computational domain
Rotating flow
Fixed end
Fluid domain
Stokes equation:
$\nabla p = \mu \nabla^2 \mathbf{u}$
$\nabla \cdot \mathbf{u} = 0$
Linear elastic material
Density, ρ_s
Young's modulus, E
Poisson's ratio, ν

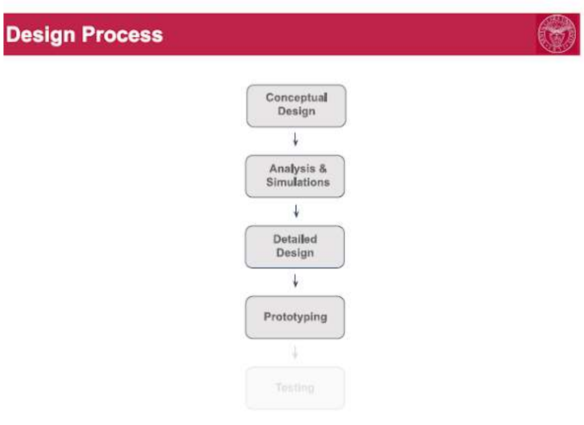

FEA: Meshing
Computational domain
Local Mesh Refinement


FEA: Meshing
Computational domain
Local Mesh Refinement
Thrust Force (N)
Degrees of Freedom
-0.29
-0.3
-0.31
-0.32
-0.33
-0.34
-0.35
0
1
2
3
4
×10^5


FEA: Simulation Results
Propulsive thrust (post-processing):
$F = \int_A (\sigma \cdot \mathbf{n})_x \, dS$
Thrust from FEA: $F \approx -1.5$ mN
Estimation of propulsion speed:
$a \approx 50$ mm
Thrust ≈ Drag
Drag ≈ $6\pi\mu aU$
⇒ $F \approx 6\pi\mu aU$
⇒ $U \approx 0.5$ mm/s


Design Process
Conceptual Design
Analysis & Simulations
Detailed Design
Prototyping
Testing


Detailed Design
Actuation subsystem
DC Motor
Arduino Nano IOT
TIP 122 Transistor
2x 3,6V batteries
Elastic Filament
Outer Magnets
Cap
O-ring
Inner Magnets
Propulsion subsystem
Electric components completely sealed
Magnetic coupling to transmit rotational motion


Design Process
Conceptual Design
Analysis & Simulations
Detailed Design
Prototyping
Testing


Prototyping: Additive Manufacturing
3D Printed Parts
Flashforge Finder 3D Printer
Polylactic Acid (PLA)
Elastic Filament
Outer Magnets
Cap
O-ring
Inner Magnets

Design Process

Conceptual Design
↓
Analysis & Simulations
↓
Detailed Design
↓
Prototyping
↓
Testing

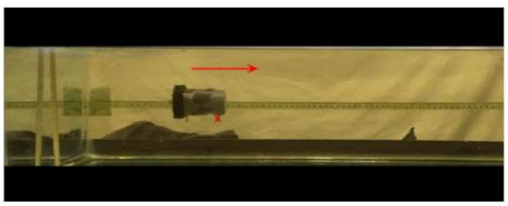
Testing: Experimental Setup

- 20 gallons of viscous corn syrup in tank
- Achieve neutral buoyancy

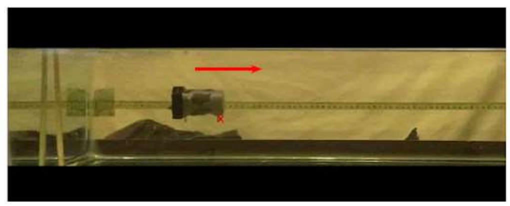
$$F_{\text{buoyancy}} = \rho_s V g > F_{\text{weight}}$$

- Setup includes a guide rail (fishing line attached to dowels on either side of tank)

Testing: Performance Characterization



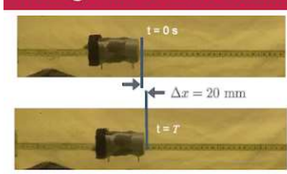
Testing: Performance Characterization



With a rotational frequency of 3 Hz

- **Net propulsion is achieved**
- **Average propulsion speed: 0.29 mm/s**
  (Same order of magnitude as prediction by simulation and analysis)

Testing: Performance Characterization



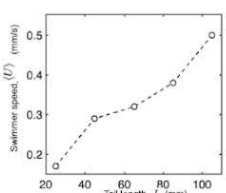
Average Propulsion Speed:

$$\langle U \rangle = \frac{\Delta x}{T}$$

- Measure the time to travel a fixed distance Δx
- Three trials for each swimmer

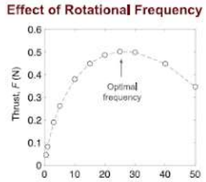
Effect of Tail Length:

Tail Length (mm)	Distance Traveled (mm)	Time (s)	Speed (mm/s)
25	20	116	0.17
45	20	69	0.29
65	20	63	0.32
85	20	52	0.38
105	20	40	0.50



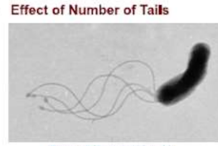
Next Steps

- **Effect of Rotational Frequency**

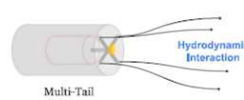


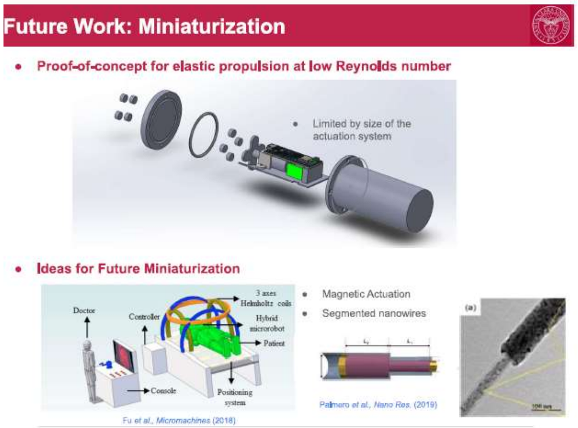
- Require motors with sufficient torques at higher speeds

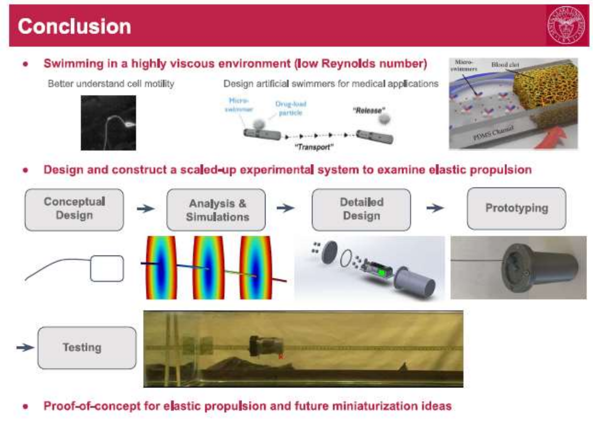
- **Effect of Number of Tails**



Hoover Lab (University of Georgia)




Future Work: Miniaturization
Proof-of-concept for elastic propulsion at low Reynolds number
Limited by size of the actuation system
Ideas for Future Miniaturization
3 axes Helmholtz coils
Doctor
Controller
Hybrid microrobot
Patient
Console
Positioning system
Fu et al., Micromachines (2018)
Magnetic Actuation
Segmented nanowires
(a)
Palmero et al., Nano Res. (2019)


Conclusion
Swimming in a highly viscous environment (low Reynolds number)
Better understand cell motility
Design artificial swimmers for medical applications
Micro-swimmer
Drug-load particle
"Release"
"Transport"
Blood clot
PDMS Channel
Design and construct a scaled-up experimental system to examine elastic propulsion
Conceptual Design
Analysis & Simulations
Detailed Design
Prototyping
Testing
Proof-of-concept for elastic propulsion and future miniaturization ideas

Appendix K: Relevant Patents

US 9,498,883 B2, “Multi-joint underwater robot having complex movement functions of walking and swimming and underwater exploration system” (Nov. 22, 2016)

US 10,107,797 B2, “Microfluidic Apparatus and Methods for Performing Blood Typing and Crossmatching” (Oct . 23 , 2018)

US 10,864,309 B2, “Heart Assist Device with Expandable Impeller Pump” (Dec. 15 , 2020)

US 10,864,162 B2, “Mass Production and Size Control of Nanoparticles Through Controlled Microvortices” (Dec. 15 , 2020)

WO 2020/052728 A1, “Method of making a biocompatible micro-swimmer, micro-swimmer and method of using such a micro-swimmer” (March 19, 2020)

Appendix L: Safety Risks and Mitigations

Hazardous Activity, Process, Condition, or Agent (identified from previous page): **Batteries**
Summary of Procedure or Tasks: Our swimmer will contain a small 3V battery pack to control the motor and arduino in the head of the swimmer.
Describe Hazards (why is the procedure hazardous or what can go wrong – what is the risk): Misused batteries can short circuit, overheat, and sometimes cause a fire. Although the voltage of the battery that we are using is usually harmless, batteries can cause electric shock which can be dangerous.
Hazard Control Measures (what you will do to eliminate the hazard or minimize risks): Keep the battery away from conductive materials (such as water). The battery is in the head of the swimmer so there is a chance that it is exposed to the silicone oil if it malfunctions, but silicon oil is actually a great electrical insulator so there is no chance of this causing a major problem. We will inspect the batteries before use to make sure that they appear to be in good condition, and only work on the swimmer's wiring when the battery is disconnected to make sure that no power is being supplied which could cause injury.

Hazardous Activity, Process, Condition, or Agent (identified from previous page): **Robotics**
Summary of Procedure or Tasks: Our swimmer will contain a motor and an arduino nano board inside the head of the swimmer. These will be wired together onto a proto board together with the battery pack mentioned earlier in the report.

Describe Hazards (why is the procedure hazardous or what can go wrong – what is the risk): The robotic components will be exposed to fluid if the head of the swimmer malfunctions. However, the fluid the swimmer will be in (silicone oil) is not conductive and therefore does not pose much of a hazard. The rotating motion that the swimmer's motor will produce can be a hazard for any jewelry, hair or loose fitting clothing in the area (can get caught on the motor crank). As with all mechanical components, there is a chance that it can short circuit causing heat, smoke or possibly fire. In addition, due to the battery connection to the robotic parts, there will be electricity running through, which can cause an electric shock if handled incorrectly.
Hazard Control Measures (what you will do to eliminate the hazard or minimize risks): The internal workings of the swimmer (circuitry) can only be handled if the battery pack is fully removed from the system. This way, the risk of electric shock is mitigated. In the area, a fire extinguisher should be present in the unlikely case of a fire due to a short circuit. Before connecting the robotic parts to power, all of the individual parts (such as the arduino, and motor) should be checked for signs of damage. To mitigate the risk of anything getting stuck in the crank of the motor, anyone working on the swimmer should tie up long hair, remove loose fitting clothing and hanging jewelry,

Hazardous Activity, Process, Condition, or Agent (identified from previous page): **Bonding / Grounding**
Summary of Procedure or Tasks: We will be using two part epoxy putty as well as araldite glue in order to assemble parts of our swimmer.
Describe Hazards (why is the procedure hazardous or what can go wrong – what is the risk): When epoxy fumes are inhaled, they can affect the nose, throat, and lungs. In addition, these strong bonding agents (the araldite glue and epoxy putty) can damage the skin if contact is made.

Hazard Control Measures (what you will do to eliminate the hazard or minimize risks):
Appropriate street clothing, gloves, a face mask, and safety glasses will be used while handling both of the bonding agents. After conducting research, the two part epoxy putty is less hazardous to inhale than traditional liquid epoxy resin, however the same precautions will be used to ensure there is maximum safety. Araldite glue is mostly hazardous to the skin and eyes, but all the PPE will be used while handing to ensure maximum safety. An eyewash station should be present in case there is contact with the eye that needs to be flushed out.

Hazardous Activity, Process, Condition, or Agent (identified from previous page):
Soldering

Summary of Procedure or Tasks:
Some soldering will be used for the robotic components in the head of the swimmer. The proto board will have wires soldered onto it from the arduino board, motor, and battery pack.

Describe Hazards (why is the procedure hazardous or what can go wrong – what is the risk):
The smoke formed from the flux can be irritating to the respiratory tract, especially for those with preexisting respiratory conditions (such as asthma). Soldering can produce "spitting" of soldering material which can damage the eyes if contact is made. The tip of the solder is very hot, which can cause damage to the skin. It can also cause fires if it is not placed on the stand when not in use.

Hazard Control Measures (what you will do to eliminate the hazard or minimize risks):
When soldering, eye protection should be used in case the solder spits.An eyewash station should be present in case there is contact with the eye that needs to be flushed out. In addition, soldering should be done in a well ventilated area to avoid too much inhalation. We can also avoid breathing in fumes by wearing a face mask, and keeping our heads to the side of, and not above our work. Also, appropriate street clothing (long pants and sleeves) should be worn just in case solder spits onto the skin (which is unlikely). Lots of attention needs to be had when soldering, as to never touch the tip of the soldering iron. The soldering iron needs to be returned to the stand when not in use (never down on the workbench). In case of a fire, a fire extinguisher should be present in the lab space.

Hazardous Activity, Process, Condition, or Agent (identified from previous page): **Hazardous Waste Generation**
Summary of Procedure or Tasks: The epoxy bonding agents mentioned in the earlier section will be used to bond certain parts of the swimmer together, such as the tail to the head. Batteries will be used to power the swimmer.
Describe Hazards (why is the procedure hazardous or what can go wrong – what is the risk): Epoxy can be corrosive and disposing of epoxy bonding agents incorrectly (such as down the drain) can cause damage to the piping system. Batteries consist of chemicals found in heavy metals, which are highly poisonous, even in small amounts, even after a battery is dead. Improper disposal can lead to these poisonous chemicals and acids leaching into land and water supplies.
Hazard Control Measures (what you will do to eliminate the hazard or minimize risks): Completely hardened epoxy is considered inert and can be disposed of regularly. Any other instance of epoxy that needs to be disposed of should be disposed of as “hazardous materials” in appropriate collection bins in the laboratory space. If the laboratory space does not have an appropriate receptacle for hazardous waste, we will be collecting the waste and taking it to a waste collection center which has a place for hazardous waste specifically. In order to properly dispose of any batteries, we will be gathering the batteries and taking them to the City of Santa Clara Battery Drop-Off site located at 1500 Warburton Avenue.

Hazardous Activity, Process, Condition, or Agent (identified from previous page): **Respiratory or Skin Sensitization**
Summary of Procedure or Tasks: We will be using a tank full of viscous fluid (silicon oil) to test our swimmer in. In addition, as mentioned in a previous section, the bonding agents used can cause respiratory or skin sensitization. Also mentioned in a previous section, we will be soldering some of the robotic components of the swimmer head.

Describe Hazards (why is the procedure hazardous or what can go wrong – what is the risk): The bonding agents used, when in contact with skin, can cause irritation and even injury if not used correctly. This is because the bonding agents are very strong, and can cause possible skin irritation upon contact, or damage to the skin if pieces of skin are stuck together. The only warning for silicon oil is that it can be irritating to the eyes (eye exposure to silicone fluids causes temporary irritation of the conjunctiva) and possibly irritating to the skin. The material is not thought to produce adverse health effects to the respiratory tract. For the soldering, the smoke formed from the flux can be irritating, a sensitizer and aggravate asthma. Soldering can produce "spitting" of soldering material which can damage the eyes.
Hazard Control Measures (what you will do to eliminate the hazard or minimize risks): Appropriate street clothing, gloves, a face mask, and safety glasses will be used while handling both of the bonding agents. After conducting research, the two part epoxy putty is less hazardous to inhale than traditional liquid epoxy resin, however the same precautions will be used to ensure there is maximum safety. Araldite glue is mostly hazardous to the skin and eyes, but all the PPE will be used while handing to ensure maximum safety. While handling the silicon oil, safety glasses will be used to avoid eye irritation. Also, gloves should be used to protect the skin on the hands, as well as to reduce the amount of residue left of hands after handling (the fluid is very viscous and is difficult to handle). When soldering, eye protection should be used in case the solder spits. In addition, soldering should be done in a well ventilated area to avoid too much inhalation. We can also avoid breathing in fumes by wearing a face mask, and keeping our heads to the side of, and not above our work. An eyewash station should be present in case there is contact with the eye that needs to be flushed out.

Hazardous Activity, Process, Condition, or Agent (identified from previous page): **Extreme Temperatures (also detailed in soldering section)**
Summary of Procedure or Tasks: We will be soldering certain parts of the swimmer circuitry to make the robot work (described in the soldering section). Soldering irons are very hot (around 400°C)
Describe Hazards (why is the procedure hazardous or what can go wrong – what is the risk): The tip of the solder is very hot, which can cause damage to the skin. It can also cause fires if it is not placed on the stand when not in use.

Hazard Control Measures (what you will do to eliminate the hazard or minimize risks):
Lots of attention needs to be had when soldering, as to never touch the tip of the soldering iron. The soldering iron needs to be returned to the stand when not in use (never down on the workbench). In case of a fire, a fire extinguisher should be present in the lab space.