HARDWARE DESIGN OF A MODULAR UNDULATORY ROBOTIC FISH WITH LINEAR ELECTROMAGNETIC ACTUATORS

A Thesis in
Mechanical Engineering

by

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ABSTRACT

This thesis details the design and development of a small multi-link robotic fish that utilizes linear electromagnetic actuators to generate undulatory motion. This design offers a few key benefits over currently employed actuation strategies in robotic fish. Firstly, the simplicity of the design allows for this actuator to be cheaply and easily manufactured. Secondly, the actuator can be utilized as a modular component in the design of various robotic fish with different segment sizes and morphology. Finally, this actuator enables our design to be easily miniaturized. These benefits enable researchers to quickly and easily explore a variety of robotic fish designs, as well as experimenting with different control and learning strategies. Additionally, 3D printing was employed to drive down the manufacturing cost and make the design more accessible and modifiable for researchers. Furthermore, custom electrical circuitry was developed to increase the modularity of the actuator. The ability to easily conduct experiments on various robotic designs further enables researchers to rapidly explore biomechanics, neuroscience and hydrodynamics in the context of aquatic locomotion.
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1. INTRODUCTION

1.1 Basics of Fish Swimming

Fish are vastly superior swimmers when compared to manmade systems. The sailfish can reach speeds of over 110 km/h, and the maximum acceleration of a pike is as high as 249 m/s\(^2\), which is over 25 g [1]. Also, fish swim silently and can turn around sharply. The outstanding performance of fish can be attributed to how they can effectively produce thrust while minimizing drag. Their streamlined body and mucous body surface both help minimize the drag force. The most important feature and where manmade systems differ distinctly, is their propulsion method.

Many fish employ oscillating foils to generate thrust and propel themselves forward. Manmade underwater vehicles driven by screw propellers typically do not achieve efficiencies above 40% where oscillating foils have shown efficiencies of up to 87% [2], [3]. This increase in efficiency is highly desirable. From the perspective of autonomous underwater vehicles (AUVs), increasing the efficiency of propulsion enables longer untethered operational times. AUVs have various maritime applications, such as: underwater exploration and mapping, wildlife observation, pipeline inspection and pollution detection, coastline security, and military operations. The clearest path to effectively employing these oscillating foils in manmade systems is to find inspiration from nature.

Bio-robotics is a highly effective method of learning what makes fish such efficient swimmers. By designing a robot inspired by fish, researchers can experimentally study multiple aspects of fish locomotion. The three main fields that bio-robotics offers key advantages to researchers are: biomechanics, neuroscience and hydrodynamics. Building a biologically inspired fish robot enables researchers to mimic the body morphology and propulsion method found in different species of fish and quantitatively evaluate its performance. From a neuroscience perspective a bio-robot can change its neurological control strategy with a simple software update. Hydrodynamically, experimenting with a fish robot in water ensures that the experiment is interacting with real physics. This cannot be verified as easily with simulation based hydrodynamic studies. With these perspectives in mind using bio-robotics to study fish locomotion is desirable. Yet this leads to a question of which type of fish should be used as a template for the robotic design.

For fish, there are generally two types of swimming methods: one using Body and/or Caudal Fin (BCF) and the other using the Medium and/or Paired Fin (MPF). BCF is used by approximately 85 % of fish species[4]. Therefore, it is the most studied form of swimming. Fish that utilize BCF locomotion can be separated into five primary modes: anguilliform, subcarangiform, carangiform, thunniform, and ostraciliform. These categories are separated by their ratio of active thrust producing body to passive rigid head as illustrated in Figure 1. Within BCF, there are roughly two kinds of motion modes: oscillatory motion and undulatory motion. Oscillatory motion in fish is achieved when the propulsor body/fin flaps in a sinusoidal motion within its range of motion, whereas undulatory motion is achieved when the propulsor body/fin forms a wave that grows in amplitude as it travels from the head to the tail. However, it is
important to note that the distinction between fish that exhibit undulatory and oscillatory motion in not always clear. The five categories of BCF fish represent a spectrum between these two propulsion modes with anguilliform exhibiting purely undulatory motion and ostraciform exhibiting purely oscillatory motion.

Figure 1: Swimming modes associated with BCF propulsion. Shaded areas contribute to thrust generation. Taken from [5].

Within BCF locomotion, two different hydrodynamic mechanisms are used to generate propulsive force, an added-mass mechanism and a lift-based mechanism [5]. To briefly summarize the added-mass mechanism, as the body of a fish forms a wave travels backwards, the body of the fish generates a force that increases the momentum of the backwards traveling water. The water then generates a reaction force on the body of the fish that propels the fish forward. A more detailed description of this mechanism is provided by Webb [6]. This is the mechanism that is employed by the anguilliform category of fish.

While the robot we are developing is capable of swimming in the various BCF modes, the current morphology is similar to that of the anguilliform category. The entire body of an anguilliform swimmer generates a large amplitude undulation. To achieve this, the body of the robot should be continuously deformed to get the required undulation. Anguilliform robots possess relatively high maneuverability because of their redundant design comprising of multiple serially connected links (multi-link) controlled by a chain of coupled oscillators which increases the degree of freedom of the robot. Because anguilliform swimmers use their entire body to swim and the other categories have a passive head component, it is relatively simple to convert an anguilliform inspired robot to the other categories [5]. To achieve the other BCF swimming modes with this design, one would have to remove some number of actuators, add a passive head component and modify the gait control system.

1.2 Existing Robotic Fish Design

A couple examples of anguilliform inspired robotic fish are NEF-II [7], [8], AmphiBot II [9], biorobotic lamprey [10], [11], amphibious snake-like robot [12] and Salamandra Robotica II [13]. These all feature motor driven actuators with the number of individual actuators varying from five to twenty. Uniquely, the snake-like swimming robot [14] developed by Kamamichi et al. was made up of three links which were actuated by means of ionic polymer metal composites.
(IPMCs) film. This is the only anguilliform swimming robot in the literature that does not utilize a motor as its actuator.

There are five general categories of actuators that are employed by the bioinspired fish: Electric motors, shape memory alloy (SMA), electroactive polymers (EAP), piezo-based actuators and electromagnetic actuators. Upon surveying the field, it becomes clear that the most common actuator in robotic fish is the motor and it is easy to understand why. Motors, whether they be DC motors or servomotors are readily available and highly optimized. However, there are some significant drawbacks when implementing motors into robotic fish. Firstly, converting the rotational motion of motors into undulatory or oscillatory motion introduces mechanical complexity and efficiency losses. Additionally, the use of motors hinders the miniaturization of the robot. The five motor driven anguilliform systems covered are all quite large. Of these systems, L. Manfredi’s et al. [10] had the smallest link length of 6 cm. Keep in mind that these robots had up to 20 links. These actuators are too large to mimic the body morphology of small to medium sized fish found in nature. However, the other four categories of actuators could address these drawbacks of motors quite well. Electromagnetic actuators, in particular, could address these drawbacks and have been implemented less than any of the other alternative actuators. Only three electromagnetic actuators are implemented as propulsion mechanism for robotic fish in the literature [15-17]. Furthermore, the systems developed by Kim et al. [15] and Liu et al. [16] rely on magnetic fields generated by large external Helmholtz coils to actuate the robots. While these systems are novel in design, they are expensive and do not provide a clear path towards their implementation in autonomous underwater vehicles.

The robotic fish developed by Qian [17] appears to be the only electromagnetic actuator found in fish robots that could feasibly be implemented in an AUV. There are some great benefits to the design; it is inexpensive, easy to manufacture and miniaturizable. This robot features permanent magnet held within a fixed electromagnetic coil. When the coil is powered a magnetic field is generated forcing the permanent magnet to rotate and align with the field. The permanent magnet is attached to swing rod that connects to a fin. By reversing the polarity of the power in the coil, the fin can achieve oscillatory motion.

1.3 Contribution of this Thesis

We are proposing an alternative electromagnetic actuator design that could be implemented in small autonomous robotic fish. Much like Qian’s actuator, our design generates movement via the alignment of the magnetic fields of permanent magnets and powered electromagnetic coils. However, our design holds two permanent magnets linearly aligned with like poles held together very closely. The close proximity of the like poles generates a strong magnetic field. Concentrically aligned outside of the permanent magnets is an electromagnetic coil that is free to move linearly along the length of the magnets. The magnetic field is diametric to the coil and therefore always orthogonal to the magnetic wires within the coil. This coil is attached to a swing rod that is pin jointed. Through this swing rod, the linear motion of the coil can easily be converted into oscillatory motion. This design is very similar to the rudder
mechanism on Park et al. [18]. However, in their robotic design they utilize this actuator simply as a steering rudder and propel the robot with a pair of SMA actuated pectoral fins.

The key difference and advantage that we believe our actuator has over Qian’s is the large magnetic field generated by the closely aligned poles of the magnets. According to Farady’s law the back electromagnetic force (EMF) induced in a coil is directly proportional to the time rate of change of the magnetic field. If a coil is oscillating through a magnetic field at a constant frequency, the back EMF is directly proportional to the strength of that magnetic field. As the back EMF in a coil increases, the resistance of that coil decreases, causing the efficiency of the coil to increase. This principle is why DC motors achieve their highest efficiency near their max velocity. With this in mind, we believe our actuator design is potentially more energy efficient than Qian’s while still being inexpensive, easy to manufacture, and miniaturizable.

We implemented this actuator into a multi-link anguilliform robotic fish with the goal of developing a research platform to explore biomechanics, hydrodynamics, and neuroscience. Additionally, we plan to eventually develop this system into an AUV. Anguilliform swimmers are an excellent candidate for AUVs due to their high maneuverability caused by their redundant actuators and their quiet swimming that is a product of their low frequency undulations. However, one of the biggest limitations of developing anguilliform swimming is the lack of a passive body to store a payload such as sensors and power supplies. Our actuator provides a solution to this limitation. By utilizing small electromagnetic actuators, we can allow for sensors to be stored within the active links of the robot. Furthermore, the speculated energy efficiency of our actuator minimizes the need for excess battery storage to power locomotion.
2. ACTUATOR DESIGN

2.1 Design Considerations

This actuator aims to provide an alternative to motor driven actuation methods commonly found in robotic fish. Motors have a few undesirable characteristics for generating undulatory motion. Firstly, they do not miniaturize well. Due to their continuous rotational motion, they fail to scale to extremely small sizes. The motor’s continuous rotation also requires a mechanism to convert its rotational output into an oscillatory output. These mechanisms add further complexity and cost to the design.

By creating an actuator that could be shrunk to a small size, the body morphologies of many smaller fish could be imitated. This allows the actuator to be used as a modular component achieving different cross-sectional areas mimicking those of fish.

A primary goal of this design was to create an inexpensive and mechanically simple actuator. This is desirable as it allows researchers to test research questions at a low cost. If the robot is inexpensive, multiple different designs could be generated with little cost. Similarly, if a design is mechanically simple it will be easy to manufacture and replicate, speeding up the research process.

2.2 Methods and Materials

This section details the design of the actuator. Table 1 reviews each component calling out manufacturing methods, material, quantity and cost per part.

<table>
<thead>
<tr>
<th>Component</th>
<th>Manufacturing method</th>
<th>Material</th>
<th>Quantity</th>
<th>Cost per part</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permanent magnet</td>
<td>Procured</td>
<td>Neodymium</td>
<td>2</td>
<td>$0.26</td>
</tr>
<tr>
<td>Electromagnetic coil</td>
<td>Procured</td>
<td>Copper</td>
<td>1</td>
<td>$1</td>
</tr>
<tr>
<td>Swing rod</td>
<td>Machined</td>
<td>Aluminum</td>
<td>1</td>
<td>$2.69</td>
</tr>
<tr>
<td>Housing</td>
<td>3D printed</td>
<td>PETG</td>
<td>1</td>
<td>$0.22</td>
</tr>
</tbody>
</table>

To generate force this actuator has two main components, an electromagnetic coil and a pair of permanent magnets, shown in Figure 2. The two magnets have like poles, held fixed in close proximity to one another, creating a strong magnetic field. The electromagnetic coil is suspended within this field. By running electricity through the coil, it generates its own magnetic field, this magnetic field aligns with the field generated by the magnets and results in an electromagnetic force moving the coil to one of the magnets. Reversing the polarity of the electricity in the coil causes the coil to be pulled to the other magnet. This generates a linear motion, however, to achieve undulation, oscillatory motion is desired. This is achieved by attaching the electromagnetic coil to a swing rod and pin jointing the rod, so it is only able to rotate. Additionally, the magnets are held at a slight angle with respect to one another so that the
coil can concentrically align with the magnet after the swing rod rotates. The actuator functionally has three states, one held to the left side, one held to the right side and one centered between the two magnets. The two side states are achieved when the coil is powered. The neutral state is achieved when no power is sent to the coil. An elastic force is built into the actuator through a silicon outer suit restoring it to the neutral position when the coil is not powered. A rendering of the three states is illustrated in Figure 3. The final design was able to achieve a ±20° range of motion from the neutral position.

![Figure 2. Electromagnetic coil (left) permanent magnet (right)](image)

![Figure 3. Rendering of actuator cross section and states](image)

### 2.3 Results

An experimental fixture was developed to measure the force generated by the actuator. A Nano17 force sensor was mounted to the output of the actuator and the actuator housing was held fixed on the other side. This fixture is shown in Figure 4. The actuator was found to generate about .01 Newtons per Volt supplied to the coil. The coil can receive 30 Volts without exceeding the current limitation of the coil. Thus, at max power, the actuator can generate approximately .3 N. It was determined that this was sufficient for propelling a small robot through water.
The actuator is 3 cm in length, 3 cm in height and 2.1 cm in width. The whole actuator can be constructed for under $5. This actuator achieves the goals of being small, mechanically simple and inexpensive.
3. ALPHA-PROTOTYPE DESIGN

3.1 Design Considerations

The primary goal of the Alpha-Prototype was to demonstrate that this actuator design could be implemented in a robotic fish as well as to explore its versatility. The design was intended to be stable, simple, inexpensive, easily manufacturable, miniaturizable, modular and resistant to water.

Special consideration was necessary in this design to build a stable system, specifically in terms of roll, pitch and buoyancy. When considering roll stability, the center of mass must be below the center of buoyancy. To achieve a buoyantly stable system the density of the robot must equate to the density of water. However, to provide pitch stability the robot was designed to be slightly buoyant allowing the surface of the water to provide the pitch stability.

The actuator is what enables this design to be inexpensive. It produces a sinusoidal oscillatory motion. In contrast, motors require complex mechanisms to achieve a similar oscillatory motion. Removing the need of such mechanisms greatly reduces the cost of the system. Additionally, the low cost was achieved by utilizing common materials and 3D printing to drive the cost of the manufacturing down.

The actuator also enables the design to be smaller than many robotic fish designs. With this in mind, the Alpha-Prototype was designed to be as small as reasonably possible. This small size reduces the power necessary to propel the robot through water and allows the actuator housing to achieve the morphological features of smaller fish.

An additional goal of this prototype was to demonstrate how this design could be modular. Each segment of the prototype contains its own actuator and could be modified to achieve different morphological shapes. Additionally, in this design, each segment could operate independently. Through the variation of the number of segments as well as their cross sectional shapes the robot could mimic the morphology of various fish found in nature.

Finally, the design had to be resistant to water as it would be using it as a medium to propel itself. This was achieved through a combination of the actuator itself being able to operate in water and the introducing a silicon outer suit that creates a seal to prevent water from leaking into the body.
3.2 Methods and Materials

This section details the design and manufacturing method of each component of the Alpha-Prototype. Table 2 reviews each component of the design calling out manufacturing methods, material, quantity and cost per part.

Table 2. Alpha-Prototype Bill of Materials

<table>
<thead>
<tr>
<th>Component</th>
<th>Manufacturing Method</th>
<th>Material</th>
<th>Quantity</th>
<th>Cost per part</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permanent magnet</td>
<td>Procured</td>
<td>Neodymium</td>
<td>2/segment</td>
<td>$0.26</td>
</tr>
<tr>
<td>Electromagnetic coil</td>
<td>Procured</td>
<td>Copper</td>
<td>1/segment</td>
<td>$1.00</td>
</tr>
<tr>
<td>Housing Cap/Swing rod</td>
<td>3D printed</td>
<td>PLA</td>
<td>1/segment</td>
<td>$0.17</td>
</tr>
<tr>
<td>Left side housing</td>
<td>3D printed</td>
<td>ABS</td>
<td>1/segment</td>
<td>$0.89</td>
</tr>
<tr>
<td>Right side housing</td>
<td>3D printed</td>
<td>ABS</td>
<td>1/segment</td>
<td>$0.88</td>
</tr>
<tr>
<td>Rubber suit</td>
<td>Injection molded</td>
<td>Silicon</td>
<td>1/segment</td>
<td>$0.55</td>
</tr>
<tr>
<td>Rubber suit sealer</td>
<td>Procured</td>
<td>Heat shrink tubing</td>
<td>1/segment</td>
<td>$0.02</td>
</tr>
<tr>
<td>Head cap</td>
<td>3D printed</td>
<td>PLA</td>
<td>1</td>
<td>$0.24</td>
</tr>
<tr>
<td>Tail</td>
<td>3D printed</td>
<td>PLA</td>
<td>1</td>
<td>$0.21</td>
</tr>
</tbody>
</table>

The first major component in the design is the housing. This consists of three subcomponents: the left side housing, the right side housing and the housing cap/swing rod. These subcomponents are illustrated in Figures 5, 6, and 7. The left and right side housings were manufactured on a Stratasys Uprint 3D printer and were printed in ABS. These subcomponents hold the permanent magnets in place as well as the pin joint of the swing rod. They also provide a path for the wires to escape the robot. The housing also acts as an additional barrier between the electrical components and the water. While the actuator can operate submerged in water, water resists the motion of the swing rod reducing the force generated, thus it is still desirable to keep the water away from the actuator.

The housing cap was manufactured on a Prusa MK3 3D printer and was printed in PLA. The prototype was first printed in ABS but due to the small surface area of printed layers on the swing rod portion of the components, the housing was prone to breaking along the layer lines. Due to this, the part was manufactured in PLA given its superior layer adhesion. Key features of the housing cap/swing rod are the clamp that holds the electromagnetic coil and the hole that holds the swing rod’s pin.
Figure 5. Rendering of Alpha-Prototype left side housing

Figure 6. Rendering of Alpha-Prototype right side housing
Figure 8 illustrates the printed and assembled housing for a single segment of the Alpha Prototype. The dimensions of this segment are 3 cm in height, 2 cm in width and 4.5 cm in length. However, the swing rod portion of the housing cap/swing rod enters the segment ahead of it making the effective length of a single segment 3 cm.

Figure 9 illustrates the actuator components in the assembled segment. Here you can see how the swing rod enters the adjacent segment. The permanent magnets are press fit into their cylindrical fixtures. The electromagnetic coil is fixed within the coil clamp using ultraviolet cured glue. There are two sheets of copper foil glued to the outer sides of the coil clamp. These sheets form solder points for wiring of the electromagnetic coil. The wiring in the coil is very thin, 44AWG, and prone to breaking from the actuator’s motion. Thus, these wires are soldered to the copper foil where they can remain stationary relative to the motion of the swing rod. Then,
the wires are covered in a layer of ultraviolet glue to ensure they do not move. Also, on these sheets of foil, two thicker 24 AWG wires are soldered. These wires are used to get power to the coil and due to their greater thickness are not prone to breaking under the oscillatory motion. Each segment displaces about 21 grams of water and a completely assembled segment only weighs approximately 14 grams. This difference in weights causes too great of a buoyancy force. To achieve nearly neutral buoyancy and roll stability, clay was placed inside of the housing cap at the bottom. This allowed the design to achieve the density necessary for near neutral buoyancy. Due to the clay being placed at the bottom of the actuator housing, the center of mass was below the center of buoyancy, achieving a roll stable system. This clay can be seen in Figure 10.

Figure 9. Alpha-Prototype assembly of actuator

Figure 10. Clay added to housing cap
Aside from the actuator housing components that make up the body of the robot, there are two other segments that are unique in design: the head segment and the tail segment. Figure 11 illustrates the head segment. This utilizes the left and right housing subcomponents as detailed earlier. Additionally, the head segment contains a modified housing cap that roughly mimics the shape of a fish’s head. This head cap is covered in a layer of epoxy to form a watertight surface covering the head segment. Figure 12 illustrates the tail segment in the Alpha-Prototype. The coil clamp and swing rod portion of the tail segment is identical to the same features in the housing cap/swing rod. However, at the end of the swing rod on the tail segment is a caudal fin that was roughly designed after that of a fish.

![Alpha-Prototype head segment](image11.png)

_Figure 11. Alpha-Prototype head segment_

![Alpha-Prototype tail segment](image12.png)

_Figure 12. Alpha-Prototype tail segment_
A silicon outer suit is utilized to seal off water from entering the robot. This suit is illustrated in Figure 13. The silicon suit serves two other purposes in the Alpha-prototype. It provides elasticity in parallel with the actuator and it houses the wires once they exit their segment of the robot. This suit is injection molded in a 3D printed PLA mold illustrated in Figure 14. The suit is composed of 30A shore hardness silicon. Each segment in the Alpha-Prototype has its own silicon suit segment and these segments are connected with heat shrink tubing to seal the seams between the silicon suit segments.

Figure 13. Alpha-Prototype segment silicon outer suit

Figure 14. Rendering of Alpha-Prototype Rubber suit segment mold
3.3 Results

The Alpha-Prototype consisted of seven segments and six actuators. Figure 15 shows the fully assembled Alpha-Prototype. The robot was 24 cm long 3 cm tall and 2 cm wide as shown in Figure 16. The Alpha-Prototype proved that the electromagnetic actuators generated a sufficient propulsive force to drive the robot. This design is significantly smaller than most undulatory fish currently designed while still maintaining a structurally sound body.

![Figure 15. Assembly of Alpha-Prototype design](image)

![Figure 16. Measured assembly of Alpha-Prototype design](image)

Testing of the prototype revealed a few issues in the design that needed to be addressed in future revisions. Firstly, and most importantly, the electromagnetic coils generate a significant amount of heat. So much so, that the PLA that was holding the coil in place was melting, causing the swing rod and clamping mechanism to deform and eventually break. The robot could be run for a short period of time (around 15 seconds) without any issues. However, this was not enough time for the experiments planned for the platform. Additionally, this interfered with the goal of creating a robot that would respond in a consistent manner.

Secondly, upon testing, it was found that a compliant tail was necessary for the robot to swim effectively. With a more complex control algorithm implemented, the robot could likely
swim with the rigid tail. However, likely due to the lack of optimization in our control mechanism we found that without the compliant tail the robot had difficulties propelling itself forward.

Finally, the wires coming from the actuators resisted the propulsive force generated by the robot. Each actuator contributes two 24 AWG wires to the robot, so with seven actuators, there are 14 wires tethering the robot. The resistive force these wires generate was significant enough to nearly negate the propulsive force generated.

In Supplemental Video 1 you can see the robot achieving an undulatory gait. But the robot does not propel itself forward. Supplemental Video 2 demonstrates a modified version of the prototype swimming at a rate of 2.7cm/s. Notable changes in this design were the compliant tail and only four actuators instead of seven. The reduction of actuators reduced the propulsive force necessary to accelerate the robot as well as reduced the number of wires resisting propulsion.
4. BETA-PROTOTYPE DESIGN

4.1 Design Considerations
The Beta-Prototype was developed to address the issues with the Alpha-Prototype design. Specifically, the Beta-Prototype aimed to make a more robust actuator implementation and introduce a compliant tail. Additionally, some changes were made in the Beta-Prototype that were not direct responses to issues in the previous revision. The actuator housing was redesigned with a uniform cross-sectional area. This made modeling and simulating the robotic design easier. Also, the actuator was redesigned to be manufactured on a relatively inexpensive 3D printer. This was intended to reduce the cost of the prototype and make the design more accessible to researchers.

4.2 Methods and Materials
This section details the modifications to the design and manufacturing methods of each component of the Beta-Prototype. Table 3 reviews each component of the design calling out manufacturing methods, material, quantity and cost per part.

<table>
<thead>
<tr>
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</tr>
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<td>Electromagnetic coil</td>
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<td>Copper</td>
<td>1/segment</td>
<td>$1.00</td>
</tr>
<tr>
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<td>6061 Aluminum</td>
<td>1/segment</td>
<td>$2.60</td>
</tr>
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<td>PETG</td>
<td>1/segment</td>
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</tr>
<tr>
<td>Right side housing</td>
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<td>PETG</td>
<td>1/segment</td>
<td>$0.13</td>
</tr>
<tr>
<td>Rubber suit</td>
<td>Injection molded</td>
<td>Silicon</td>
<td>1/segment</td>
<td>$0.55</td>
</tr>
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<td>Rubber suit sealer</td>
<td>Procured</td>
<td>Heat shrink tubing</td>
<td>1/segment</td>
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<tr>
<td>Head cap</td>
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<td>PLA</td>
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</tr>
<tr>
<td>Tail</td>
<td>3D printed</td>
<td>PETG/silicon</td>
<td>1</td>
<td>$0.35</td>
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Unlike the Alpha-Prototype, the segment housing in the Beta-Prototype only consist of 2 components, a left and right side housing. Renderings of these components are shown in Figures 17 and 18. These components are 3D printed on a Prusa MK3S in PETG. PETG was chosen to replace the PLA due to its superior heat tolerance. Additionally, the housings are were held together with m2 screws rather than with a snap fit as in the Alpha-Prototype. This provided a more robust system and allowed for easier assembly and modification.
The swing rod is a separate component in the Beta-Prototype. It is machined out of aluminum which allows the robot itself to be much more resistant to heat right at the source, the electromagnetic coil. The aluminum additionally acts as a heat sink to pull the heat away from the coil. A rendering of the swing rod and coil is shown in Figure 19 where the red is the aluminum swing rod. The swing rod is press fit into the right side housing and is pinned in place with an m2 screw and a lock nut. This whole assembly can be seen in Figure 20.
The Beta-Prototype also has a custom head segment much like that of the previous prototype. Again, the head is covered in epoxy to seal the head from leaking water. Like the other segments in the Beta-Prototype, the head segment housing is held together with a m2 screw. This segment is shown in Figure 21.

One of the most notable changes in the Beta-Prototype is the redesigned tail segment. The skeletal structure of the tail segment is 3D printed in PETG. A compliant portion of the tail is added with the same silicon that makes up the rubber suit. A rendering of the tail segment, its 3D printed skeletal structure and an image of the manufactured tail can be seen in Figures 22, 23 and 24, respectively.
Figure 22. Rendering of Beta-Prototype tail segment

Figure 23. Beta-Prototype tail skeletal structure

Figure 24. Beta-Prototype tail segment
4.3 Results
This system was developed featuring four actuators. The dimensions of the robot were 18.6 cm in length, 1 cm in width and 3 cm in height. This entire robot was built for under $20. As shown in Supplemental Video 3 the robot was able to swim at a speed of 2.9 cm/s. This design has 8 wires exiting the head of the robot. With the increased range of motion of the actuators, the robot was able to achieve an S-shaped swimming gait as illustrated in Figure 25.

![Figure 25. Rendering of Beta-Prototype assembly without rubber suit](image)

Figure 26 illustrates the assembled Beta-Prototype skeletal structure. Note that each actuator has two wires exiting its housing. With 6 actuators as shown in this figure, a bundle of 12 wires tethers the robot to its power supply.

![Figure 26. Beta-Prototype skeletal assembly and wire path](image)

Figures 27 and 28 illustrate the side and top view of a fully assembled Beta-Prototype. This was the configuration used in testing the Beta-Prototype design.
The Beta-Prototype effectively mitigated the heat issues found when testing the Alpha-Prototype. Actuators were able to be run for 5 continuous minutes while supplied with 15V without any degradation of the integrity of the actuator. The actuator was also tested at 30V for short 30 second intervals, again without experiencing any heat related issues.

The other changes in the mechanical design of the robot improved the performance and durability of the system. The compliant tail redesign effectively increased the propulsive force generated by the robot. Also, the addition of fastening hardware to assemble the actuator housing made the design much simpler to assemble and resulted in a more rigid housing assembly.

The only major issues that persisted in the Beta-Prototype were the issues relating to the wiring of the actuators. It was difficult to feed all of the wires through the silicon wire path and nearly impossible to disassemble the robot without destroying the silicon outer suit in the process. Furthermore, each actuator contributed two wires to the wire tether of the robot. This limited the number of actuators that could be used without producing and excessive resistive force due the large bundle of wires exiting the head of the robot.
5. FINAL SYSTEM DESIGN

5.1 Design Considerations
The final revision for the system was an update to the electrical systems within the robot. The goal of this update was to reduce the number of wires necessary to control the robot. Additionally, this was intended to increase the modularity of a single segment of the robot. Furthermore, the electrical upgrade aimed to simplify the assembly process by allowing the wires to pass directly through the actuator housings, rather than through the rubber suit segments.

5.2 Methods and Materials
This section details the modifications to the design and manufacturing method of each component changed in the final system design. Table 4 reviews each component of the design calling out manufacturing methods, material, quantity and cost per part.

<table>
<thead>
<tr>
<th>Component</th>
<th>Manufacturing Method</th>
<th>Material</th>
<th>Quantity</th>
<th>Cost per part</th>
</tr>
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<tbody>
<tr>
<td>Permanent magnet</td>
<td>Procured</td>
<td>Neodymium</td>
<td>2/segment</td>
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<td>Copper</td>
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<td>$1.00</td>
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<td>Swing rod</td>
<td>Machined</td>
<td>6061 Aluminum</td>
<td>1/segment</td>
<td>$2.69</td>
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<td>3D printed</td>
<td>PETG</td>
<td>1/segment</td>
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<td>PETG</td>
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<tr>
<td>Rubber suit</td>
<td>Injection molded</td>
<td>Silicon</td>
<td>1/segment</td>
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</tr>
<tr>
<td>Rubber suit sealer</td>
<td>Procured</td>
<td>Heat shrink tubing</td>
<td>1/segment</td>
<td>$0.02</td>
</tr>
<tr>
<td>Head cap</td>
<td>3D printed</td>
<td>PETG</td>
<td>1</td>
<td>$0.08</td>
</tr>
<tr>
<td>Tail</td>
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<td>1</td>
<td>$0.35</td>
</tr>
<tr>
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<td>1/segment</td>
<td>$0.60</td>
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<td>1/segment</td>
<td>$0.27</td>
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<td>H-Bridge</td>
<td>Procured</td>
<td>N/A</td>
<td>1/segment</td>
<td>$2.25</td>
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<td>N/A</td>
<td>2/segment</td>
<td>$0.10</td>
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<tr>
<td>4.7 kΩ resistor</td>
<td>Procured</td>
<td>N/A</td>
<td>1/segment</td>
<td>$0.08</td>
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</table>

In an effort to reduce the number of wires coming out of the robot and to increase the modularity of the design, custom circuitry was added inside of each actuator housing. A custom printed circuit board (PCB) was developed to wire and package the circuit components. The PCB circuit schematic can be seen in Figure 29. A rendering of the top and bottom side of this printed circuit board can be seen in Figure 30.
To reduce the number of wires tethering the robot, serial communication was implemented. This was achieved by embedding a shift register chip inside of each actuator housing. However, these shift registers themselves are not able to directly drive the electromagnetic coils in the actuator as the coils require more voltage than the shift register can provide. So, a H-bridge chip is also embeded into each actuator housing. The shift register sends the control signals to the H-bridge and the H-bridge then controls the voltage being sent to the coil. Both of theses chips are mounted to the custom PCB as shown in Figure 31. This control
circuitry requires six wires to be run along the length of the robot. With these six wires, an indefinite number of actuators can be daisy chained together and controlled independently.

Figure 31. Final System Design custom PCB top and bottom side

The actuator housing had to be modified slightly to accommodate the PCB. A slot was added into the bottom half of both sides of the actuator housing to hold the PCB in place. Additionally, with this new circuitry, the wire path had been changed. Previously two wires would exit every actuator housing, enter the wire path in the elastic suit, and then exit at the front of the robot. Now, the six wires travel along the bottom of the actuator housings. The actuator was again 3D printed in PETG on a Prusa MK3S. The updated actuator housings can be seen in Figures 32 and 33.

Figure 32. Rendering of Final System Design left side housing
Figure 33. Rendering of Final System Design right side housing

Figure 34 illustrates an assembled segment of the Final System Design. The electronics at the bottom of the segment provide the roll stability in this design. This PCB cannot operate in water, to remedy this the PCB is covered in a layer of silicon conformal coating which effectively waterproofs the design.

Figure 34. Final System Design segment assembly

The Final System Design also had a slightly modified head segment to account for the PCB and new wire path. This head segment is shown in Figure 35.
5.3 Results
This system was developed featuring four actuators. The dimensions of the robot were 18.6 cm in length, 2.5 cm in width and 3.9 cm in height. This entire robot was built for $34. It was able to swim at a speed of 2.85 cm/s. This design only has six wires exiting the head of the robot. A top and side view of the skeletal assembly of the robot can be seen in Figure 36. Note the modifications in the wiring of this design. The Beta-Porotype had the same number of actuators and required eight wires to control that robot. With this design the six wires can control an indefinite number of actuators. Also, note that the wire path now passes through the actuator housing. This simplified the assembly and disassembly process of the robot as the wires previously had to pass through the silicon outer suit. The system with the external rubber suit can be seen in Figure 37.
Figure 36. Final System Design skeletal assembly side and top view

Figure 37. Final System Design side and top view
Figure 38 illustrates the full range of motion of the Final System Design. With each actuator achieving a ±20° range of motion between four actuators the head and tail segments can achieve an 80° difference in heading angle.

Figure 38. Final System Design actuator full range of motion

Figure 39 displays the robot starting from rest and achieving a velocity of 2.85 cm/s or .17 body lengths per second. A video of this experiment can be seen in Supplemental Video 4. This gait resulted in a cost of transport of 689 JN⁻¹m⁻¹, where when swimming at an optimal velocity, fish species have been shown to achieve costs of transport within the range of 0.15-15 JN⁻¹m⁻¹ [19]. While this is a considerably large cost of transport, this cost was the result of a rudimentary control strategy. Each actuator was powered with a square wave and a constant phase lag from the leading actuator. Upon control strategy optimization, we believe that this system could achieve a much more efficient swimming gait and a higher velocity.

Figure 39: Final System Design swimming from rest
6. CONCLUSION

This research aimed to develop a robotic fish that could be utilized as a research platform to explore questions in biomechanics, hydrodynamics and neuroscience in the context of aquatic locomotion. The robot that was developed displayed potential to rapidly and inexpensively generate experimental set-ups capable of exploring many research questions in these fields. There is a wide breadth of future work that could be done to further this research.

Biomechanically, there are multiple features of this design that could be easily modified and tested. The caudal fin implemented in this design was very rudimentary. An optimal design of this feature could be explored by varying the shape, material and stiffness. The silicon outer suit is also an area that would be interesting to explore. By modifying the material and thickness of the elastic outer suit the passive viscoelastic properties of the robot could be tuned. Similarly, springs could be added to the actuators to accurately control the elasticity of each joint. More complex biomechanical experiments could also be conducted. For example, by modifying the number of actuators and their respective cross-sectional shapes, the body morphology of various fish species found in nature could be mimicked. The small size of this actuator, compared to common motor driven designs, allows this design to mimic the body morphology of smaller fish found in nature. Additionally, due to the simplicity of the actuator design, the actuator can be easily scaled up with the addition of larger permanent magnets and larger electromagnetic coils. More powerful actuators would be desirable for driving systems that mimic the body morphology of larger fish.

The platform also offers great potential in terms of researching neurological control signals. Bioinspired robots are great candidates for validating neurological control models, as these control models can be directly implemented into the robot. For example, another researcher in our lab is developing a central pattern generator (CPG) for controlling an undulatory fish like robot in a simulated environment. The parameters in this CPG are being learned through machine learning methods. Once optimal parameters are learned in the simulated environment, this CPG could be implemented as a control strategy for the physical robot and its performance can be experimentally validated. This is just one example of a control system that could be learned in a simulated environment and validated in the system. However, there are many other control strategies to explore, from a simple sinusoidal driving signal to more complex, higher level control, such as developing turning gaits. To learn optimal parameters in for controlling the robot in a simulated environment, a hydrodynamic model must be used to train the control strategies.

This platform can validate hydrodynamic models as well. Rather than relying on simulations that are always just approximations of fluid mechanics, researchers can develop experimental setups utilizing the robot to validate and update parameters in hydrodynamic models. Currently, only data based on the robot’s physical body can be easily collected such as swimming velocity or joint angles. However, this project is part of a collaboration with the University of Houston where a stretchable pressure sensor is being developed for this system. This sensor is to be embedded in the elastic suit which would provide pressure data on the
surrounding fluid. Once implemented, an array of pressure sensors of this nature would enable experimental data collection that could be used to optimize hydrodynamic models.

Aside from being an excellent tool for rapidly exploring these scientific fields, the robot also shows potential as an autonomous underwater vehicle. To achieve autonomous functionality, significant development of the robot would be required, primarily onboard power and control systems would need to be developed. As an autonomous vehicle this platform could be used to imitate and explore behavior found in nature such as schooling or predator/prey chases.

Further down the development timeline, once a production design of the robot is finalized, the manufacturing methods for components could also be updated to support a larger and more rapid production. For example, 3D printing was selected to manufacture the actuator housing so that researchers could rapidly prototype new designs. However, with a production design, injection molding of the actuator housing would allow a greater variety of material to be used with superior mechanical properties and at a lower cost per part. Similarly, production manufacturing methods at a greater volume would reduce the cost of the more expensive components such as the aluminum swing rod and the custom PCB.
BIBLIOGRAPHY


