Designing a Lorentz Force Actuator for a Robotic Tuna

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Contents

List of Figures

1 The Olin Robotic Tuna Research Project

1.1 Introduction to the Olin Robotic Tuna Research Project

The long-term goal of the Olin Robotic Tuna research project is to design a robotic tuna capable of completing a trans-atlantic voyage. To achieve this goal, the project has been divided up into three phases, starting with a one-man launchable robotic tuna and ending with a much larger version capable of housing the required infrastructure for a long trans-atlantic voyage.

The project is currently still in phase 1. Last summer (summer 2014), we developed a proof of concept version of the robotic tuna to prove that our actuation concept was feasible. In the fall of 2014, we then proceeded to develop some of the software required for autonomous operation of the robotic tuna. This semester, we refocused our research efforts on designing a more efficient verison of the propulsion system for the robotic tuna.

1.2 Why a Tuna?

The main reason for designing a robotic tuna is propulsion efficiency. Biological tuna fish have a highly efficient method of propulsion that wastes very little energy compared to any existing method of propulsion used on sea vessels today. This efficiency is achieved through several key modifications:

1. Eliminating Water Rotation

Despite the wide variety of boat propellers and motors available, most conventional water propulsion methods essentially rely on a spinning propeller pushing water out the back of the sea vessel in order to propel the sea vessel forward. While this is a great propulsion method, the use of propellers means that, in addition to pushing water out behind the sea vessel, the water is also being rotated in the vertical plane by virtue of being in contact with the rotating propeller blades. However, to propel a sea vessel forward, the only motion that matters is the straight motion of the water out the back of the vessel. This means that all the energy that is spent to rotate the water is wasted energy since the rotational motion is unnecessary.

In a biological tuna, however, there is no such rotation of the water and so the tuna immediately gains this energy saving.

2. Vortex Manipulation

The second, and more intriguing, reason that a tuna can achieve such high propulsion efficiency is that a tuna detects and manipulates vortices occuring around it in order to increase the propulsion forces acting on it.

As a tuna swims through the water, small swirls of water, known as vortices, are generated that travel down the side of its body as shown in the figure below:

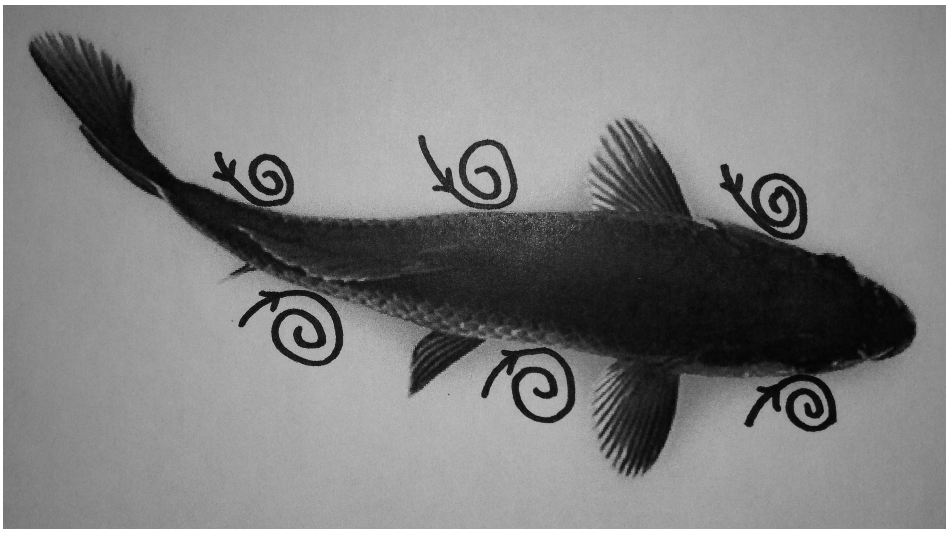

Figure 1: Vortices along the body of a tuna

When these vortices reach the tail, the tuna positions its tail appropriately such that the tail is in the correct position to be pushed on by the vortices as the vortices leaves the tail of the tuna. This allows the tuna to gain additional propulsion from these vortices. The following diagram[1] illustrates this:

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[1] Diagram from Triatafyllou, M. S. & Triatafyllou, G. S. (1995). An Efficient Swimming Machine, Scientific American, 272.3, 64-71

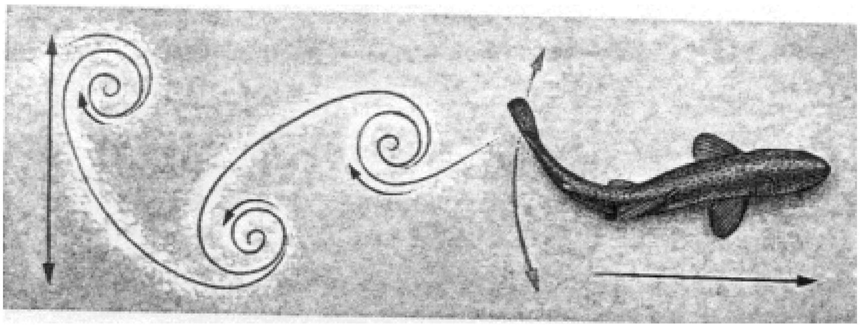


Figure 2: Vortex shedding from the tail of a fish

Thus, because the tuna is capable of making use of the movement of the water around it to achieve additional propulsion, it is able to further reduce the amount of energy that is wasted in water movement that does not contribute to propulsion.

2 The Current Robotic Tuna

The current robotic tuna is shown in the figure below:

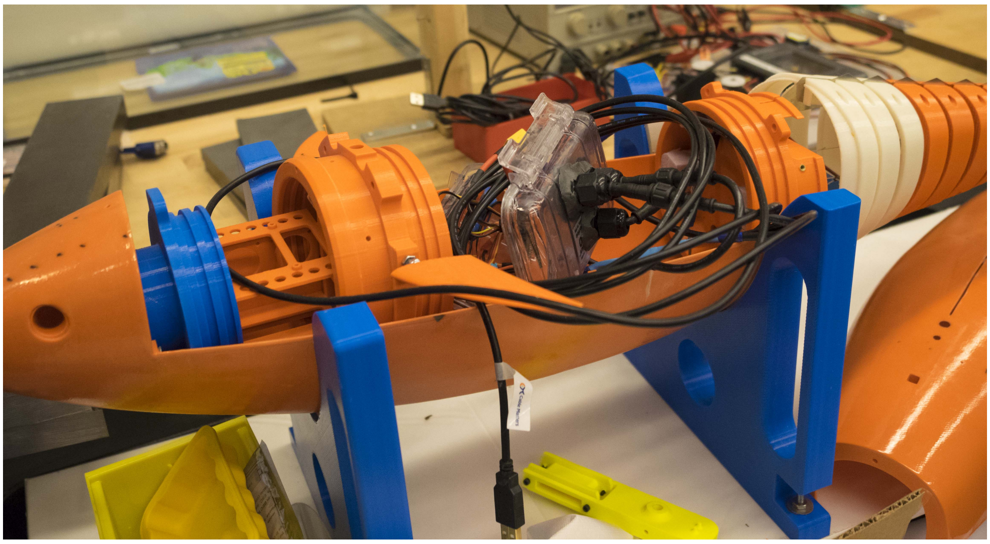


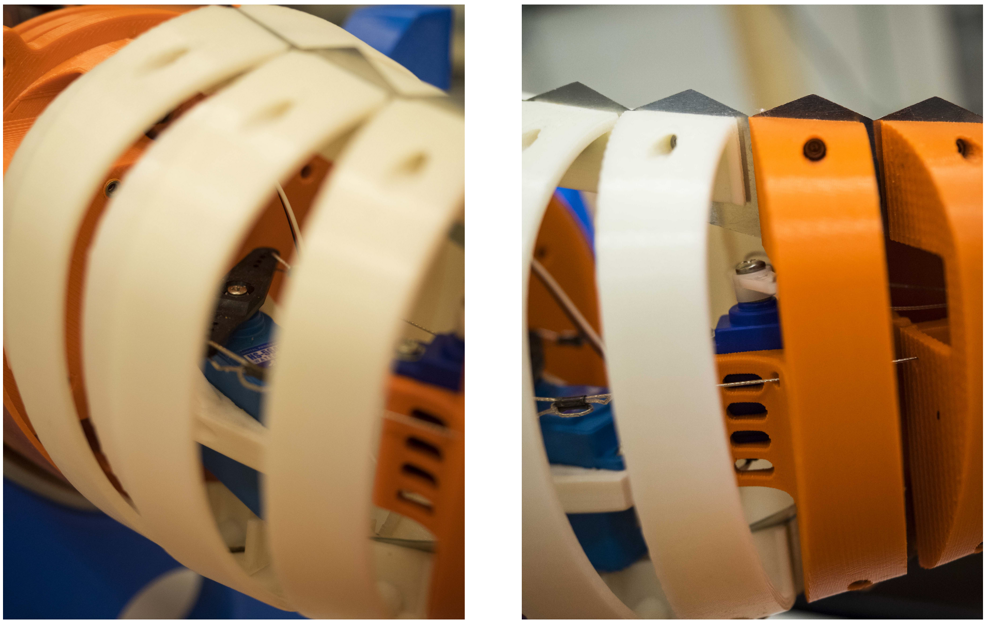
Figure 3: The current version of the robotic tuna

For the research this semester, we were particularly interested in the efficiency of the propulsion system for the fish. The propulsion system designed in the summer of 2014 is shown in the figures below:

(a) The whole tail section

(b) Close-up view of the two servos powering the tail section

Figure 4: Views of the tail section of the current version of the robotic tuna



(a) Propulsion servo

(b) Steering Servo

Figure 5: Close-up views of the servo that delivers propulsion power (left) and the servo that aids in steering (right)

In essence, the tail designed in the summer of 2014 had two servos powering it. One servo was mounted to the base of the tail and this servo served as the main source of power for propelling the fish forward. This servo essentially performed the function of a propeller on a typical boat. The other servo was mounted in the fourth section of the tail and was used to control only the last three sections of the tail to help steer the fish where necessary. This servo essentially performed the function of a ruder on a typical boat.

Although this design was useful as a proof-of-concept, using the servos in this manner is extremely inefficient. As such, in order to advance toward the goal of a highly efficient robotic tuna, we wanted to design a significantly more efficient tail.

3 Increasing Propulsion Efficiency

To begin designing a more efficient propulsion system, we first began by comparing the way a biological tuna generates propulsion to the way the current robotic tuna achieves propulsion to figure out where the largest mechanical losses were present. As a result, we realized that, unlike the biological fish, the robotic tuna must continue to supply energy to oscillate its tail. It is therefore unable to take advantage of resonance and natural frequencies of vibration to reduce the amount of energy required to sustain the oscillation of its tail. For this reason, we concluded that traditional methods of actuation that relied on contact forces would not be suitable because such actuation methods would not be capable of being ”uncoupled” in order to allow the tail to achieve resonance. To solve this problem, we turned to magnetism and lorentz force actuators.

3.1 Magnetism and Lorentz Forces

Lorentz force is the force that a charged particle will experience when it is placed in a magnetic or electromagnetic field. Equally, what this means is that a wire or a coil of wire will also experience a force when a magnetic field is applied across it. A diagram of a simple set up with a wire placed in an applied magnetic field is shown in the figure below[2]:

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[2] Diagram obtained from `http://www.antonine-education.co.uk/Pages/Physics_4/Magnetism/MAG_01/mag_field_1.htm`

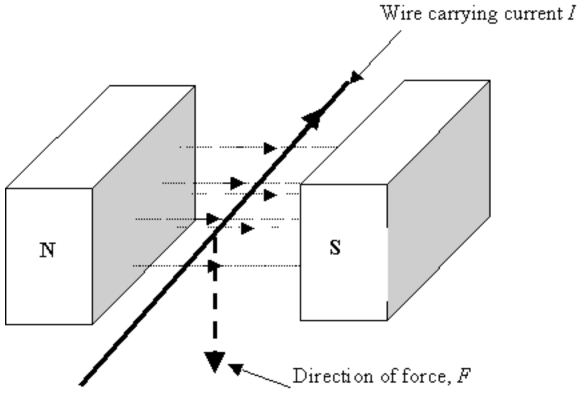

Figure 6: Diagram of a simple wire placed in a magnetic field

As can be seen in the figure, the force that the wire experiences is known as a lorentz force. Assuming the wire is placed perpendicular to the direction of the magnetic field, the equation that governs the magnitude of the force is then:

$$\vec{F} = \vec{I}L \times \vec{B} \tag{1}$$

where $\vec{F}$ is the force acting on the current-carrying wire, $\vec{I}$ is the current through the wire, L is the length of the wire exposed to the magnetic field and $\vec{B}$ is the magnetic field.

As such, given Equation 1, the force experienced by the wire can be changed either by changing the current, changing the length of the wire exposed to the magnetic field or by changing the strength of the magnetic field itself.

3.2 Efficiency

In addition to being able to generate the necessary forces, we also want the lorentz force actuator to do this as efficiently as possible to minimize the energy consumption. With reference to Figure 6, we can imagine that an actuator employing lorentz forces might have the following losses:

1. Losses due to resistance in the wire as the current moves through
2. Mechanical losses as the wire moves due to the force it experiences
3. Losses due to magnetic flux from the magnetic field escaping to the surroundings

Losses in the wire and mechanical losses are almost unavoidable and are typically relatively small. As such, we turn our attention to losses due to magnetic flux escaping into the surroundings.

Since lorentz force actuators require a magnetic force in order to function, the magnetic field is a source of energy for the actuator. As such, when magnetic flux is lost to the surroundings, we are essentially losing energy to the surroundings that could have been used to do useful work in moving the wire. In order to minimize these losses, it is therefore important to ensure that the magnetic flux is contained and only allowed to escape across the air gap where the force needs to be generated. In this way, loss of magnetic flux to the surroundings is minimized.

As it turns out, the most common method of containing magnetic flux is to create what is known as a magnetic circuit. Just as a typical electrical circuit has electrons flowing through it, a magnetic circuit has magnetic flux flowing through it. A typical magnet placed in air will have magnetic field lines around it as shown in the figure below[3]:

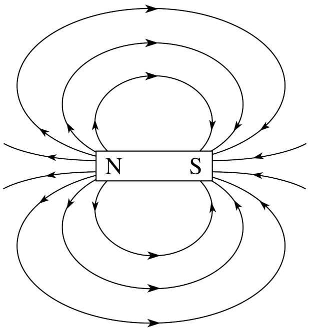

Figure 7: Field lines of a magnet in free air

As can be seen in Figure 7, when a magnet is left in air, the magnetic field lines form loops that get larger the further they are away from the magnet. As such, magnetic flux is being freely lost into the environment when a magnet is left in air and this is all lost energy. We can minimize this lost magnetic flux by placing a ferrous material such as iron near the magnet such that the field lines will preferentially enter the ferrous material instead of being lost to the environment as shown in the figure below[4]:

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[3] Diagram obtained from `http://physics.stackexchange.com/questions/143119/why-in-a-solenoid-do-the-magnetic-field-lines-resemble-that-of-a-bar-magnet`

[4] Diagram obtained from `http://www.globalspec.com/reference/81215/203279/1-22-magnetic-circuits`

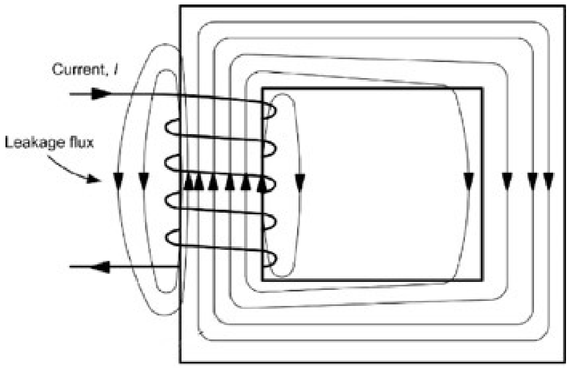

Figure 8: Diagram of magnetic circuit in a ferrous material

As can be seen in Figure 8, there is much less magnetic flux lost to the environment because it is now contained within the ferrous material. We can then take advantage of this mganetic circuit in a lorentz force actuator by cutting a hole out of the loop formed by the ferrous material and allowing the magnetic flux to flow across that air gap. By doing this, we have maximized the magnetic field strength across the air gap. Therefore, if we place a current carrying wire in the air gap, we will have maximized the lorentz force experienecd by that wire.

4 Actuator Design

For our design, we were inspired by the design of hard disk arm actuators. An image of one is shown below[5]:

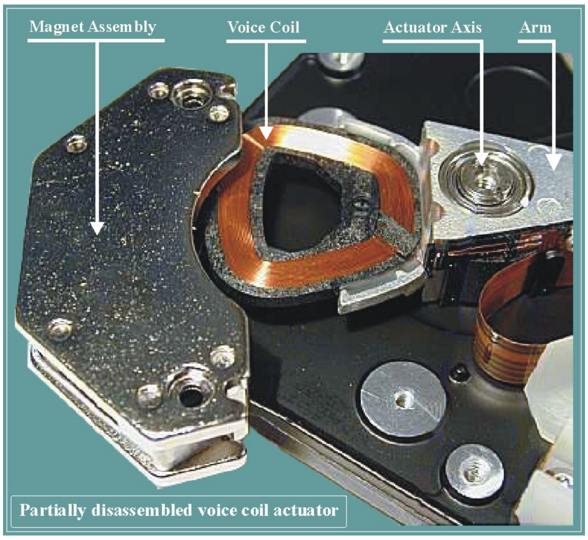

Figure 9: Diagram of a Hard Disk Drive Arm

As can be seen in the figure above, the voice coil is a coil of magnet wire through which a current is passed. The voice coil then sits between a pair of magnets, one positioned above and one positioned below the voice coil. These magnets thus apply a magnetic field across the voice coil. When a current is passed through the voice coil, the voice coil experiences a force which causes it to pivot around the actuator axis and move the arm.

This seemed to be a good concept for what we expected for the actuator for the fish. The oscilating back and forth motion needed to actuate the sections of the tuna tail could be achieved by swinging the arm back and forth. However, we now needed to figure out how to design such an actuator to be as efficient as possible.

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[5] Image from `http://www.kepcil.com/kepcilin/harddisk/hdslider/bigcoil1.jpg`

4.1 Desired Motion and Proposed Control Scheme

The design of the actuator began with deciding on the desired motion we want to achieve and how the control system could be designed to achieve this. For this prototype, the goal was to design an actuator that would allow the actuator arm to oscillate back and forth in a rotary motion. Doing so would therefore allow us to attach the oscillating part of the actuator to a section of the fish tail and therefore oscillate the tail.

In terms of the control scheme, one can imagine that this desired motion is similar to a child on a swing. The child rides on the swing by swinging back and forth in essentially an oscillatory motion. In order to keep the swing moving, the child must deliver impulses of velocity at some point in the motion by swinging their legs out. Therefore, for the actuator to achieve sustained oscillatory motion, it too must deliver impulses of velocity at some point in its oscillatory motion.

In terms of a control scheme, however, the key question is when during the oscillation does the impulse of velocity need to occur? To answer this question consider the velocity-position plot of the motion as shown in the figure below:

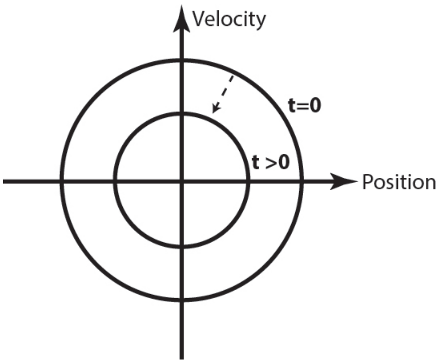


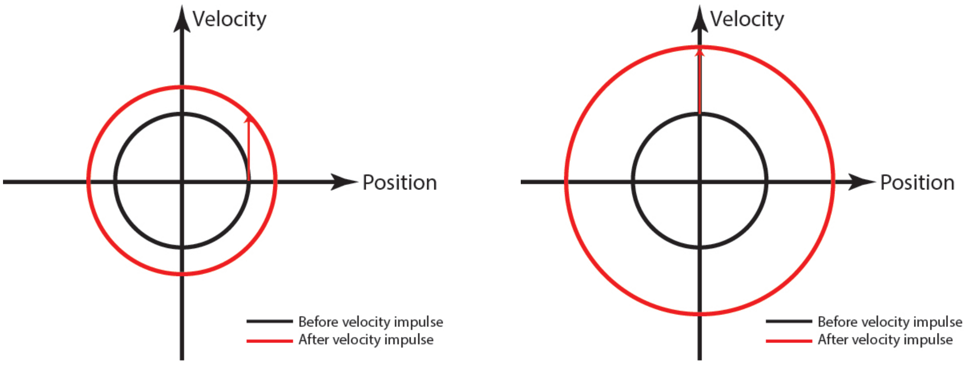
Figure 10: Conceptualized velocity-position plot of the actuator as it oscillates.

As can be seen in Figure 10, after starting at some initial position with some initial velocity at t=0, frictional and other losses will cause the oscillation to decrease in amplitude, assuming no external force is applied to restore the oscillation. As such, the circle traced on the velocity-position plot will shrink in radius as shown by the circle labeled t>0.

To apply a restoring force, one could imagine that the two positions that would allow the velocity impulse to have the largest impact on the motion are:

1. Deliver the velocity impulse at equilibrium position where position is zero and velocity is maximum; or
2. Deliver the velocity impulse at the extreme positions where velocity is zero and posiiton is maximum

The effects of each possible choice are shown in the graphs below:



(a) Velocity impulse delivered at maximum position, zero velocity.

(b) Velocity impulse delivered at maximum velocity, equilibrium position.

Figure 11: Velocity-position plots of the actuator oscillation with the velocity impulse delivered at different points

As can be seen in the above figure, applying the velocity impulse at the equilibrium position results in the largest change in oscillation. As such, in the mechanical design of this actuator, the magnets should be placed at the equilibrium position of the oscillation in order to be able to deliver a pulse of velocity at equilibrium to sustain the oscillation.

4.2 Overview of the Mechanical Design

The prototype of the actuator designed during this research period is shown in the figure below:

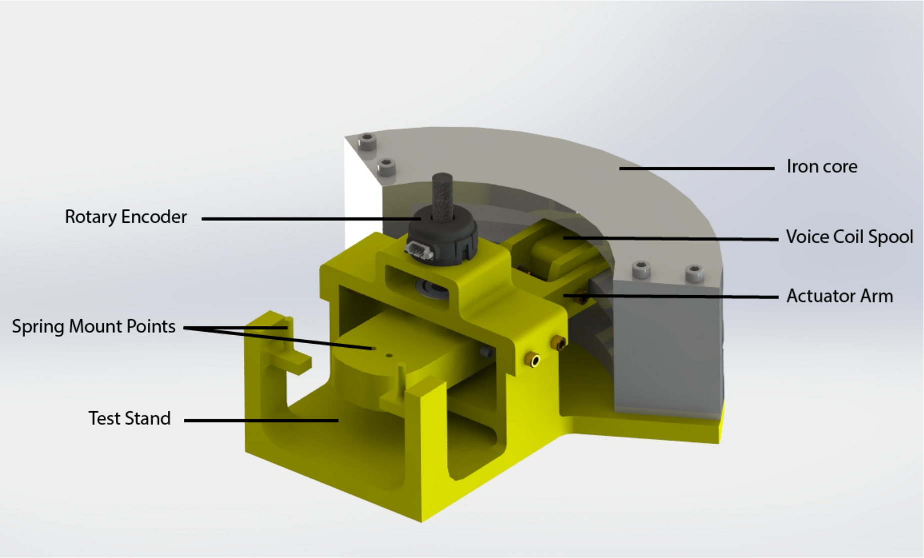


Figure 12: Render of the prototype actuator

The actuator has four main mechanical components:

1. The iron core, which consists of three pieces: the upper frame, the magnetic shield and the lower frame. The purpose of the iron core is to contain the magnetic flux within it and minimize the loss of magnetic flux into the surroundings.
2. The voice coil spool that will hold the magnet wire voice coil. When current is passed through that magnet wire, a resulting force will act on the voice coil spool.
3. The actuator arm that holds the voice coil spool. When current is applied to the voice coil, the force experienced by the voice coil spool will move the arm and cause it to swing back and forth
4. The test stand in this prototype represents the supporting structure that will be needed to mount the components that make up the actuator.

The following sections will now explain the design of each component in detail.

4.3 The Iron Core

The iron core is one of the most important components in the actuator and the actuator could not function without it. As discussed in section 3.2, in order to for the actuator to be as efficient as possible, there must be a loop of ferrous material that is able to capture the magnetic flux produced by the magnet in order to contain it and concentrate it across the air gap where it is required. This minimizes the energy losses to the environment. As such, the iron core makes up part of the structure of the actuator and the magnets that will be used to generate a magnetic field are mounted to this iron core. The figure below shows this configuration:

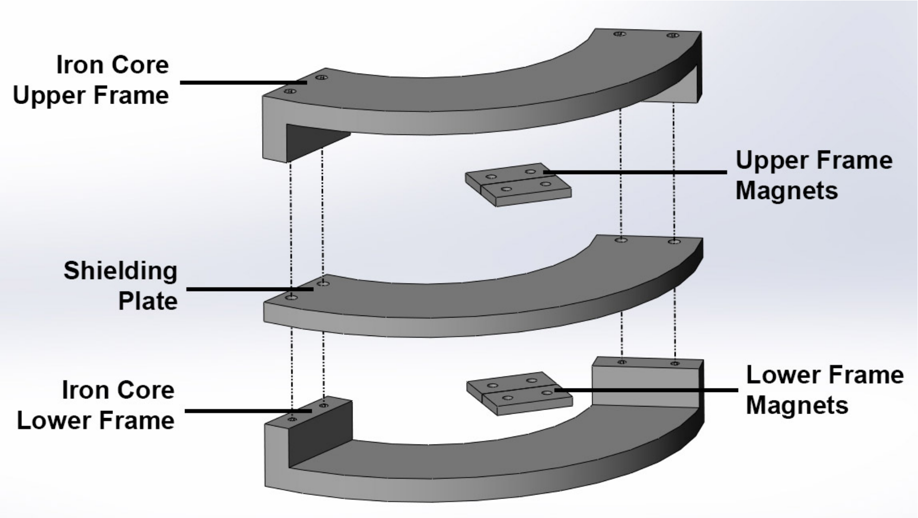


Figure 13: Exploded view of the iron core

As can be seen in Figure 13, the loop of ferrous material that contains the magnetic circuit is made up of the upper frame, shielding plate and lower frame. The magnets that provide the magnetic flux for the system are then mounted to the upper and lower frame and the voice coil fits around the shielding plate. With this configuration, the magnetic flux from the magnet crosses the air gap either between either the upper frame and shielding plate or between the lower frame and shielding plate. Either way, the flux then ends up in the lower shielding plate where it can then travel back around to the upper or lower frame to form a complete magnetic circuit. As a result, this design should concentrate the magnetic flux in the air gap where the voice coil will be located to maximize the force generated. In addition, because the magnets are mounted on the interior of the iron core, the loss of magnetic flux to the surroundings should be minimized.

4.4 The Voice Coil

In this prototype, the dimensions of the voice coil were designed such that the lorentz force generated was enough to counteract the springs that are being used to provide restoring force (see section 4.5 for more details on how springs are involved in the design). As such, it was necessary to calculate the dimensions of the voice coil in order to ensure that the actuator would work as expected.

To start, the table below lists some of the system parameters that have been set and cannot be changed:

Parameter Description	**Parameter Value**
Maximum Spring Force	0.76lbf ≈ 3.4N
Length of Voice Coil Exposed to Magnetic Field	2.54cm = 0.0254m
Magnetic Field Generated by Magnets	6000 Gauss ≈ 0.6 Tesla

Table 1: Table of set parameters for the voice coil

Using Equation 1, we can then express the force equation as follows:

$$\vec{F} = 3.4 = (0.6)(0.0254)NI \tag{2}$$

where N is the number of turns on the coil and I is the current flowing through the magnet wire that will be wound around the voice coil holder.

Thus,

$$NI = \frac{3.4}{(0.6)(0.0254)} \approx 223.1 \tag{3}$$

Therefore, we have two factors in the design of the voice coil that we can manipulate: the number of turns on the voice coil and the current flowing through it. However, the magnet wire has a fixed maximum current rating that should not be exceeded so we do not have absolute freedom over that parameter.

For this prototype, we are using 20AWG wire which has a maximum current rating of 11 amps under chassis wiring conditions (exposed to air to cool). Given that we want a Factor of Safety (FOS) of 2, therefore, the maximum current load through the wire should be:

$$A_{max} = \frac{11}{2} \approx 5.5\text{A} \tag{4}$$

Given that maximum current rating, the number of turns needed to generate sufficient force is:

$$N = \frac{223.1}{5.5} \approx 41 \text{ turns} \tag{5}$$

Therefore, to add additional FOS, we should use 50 turns in the voice coil.

Using this, we can now calculate physical dimensions of the holder around which the magnet wire will be wound. 20 AWG magnet wire has a wire diameter of 0.032in. If 50 turns were laid out in one single row, the length would be $50(0.032) = 1.6$in. This would be a ridiculous width given the dimensions of the rest of the prototype. However, we can stack multiple layers of coils. As such, if we use a two-layer configuration, the width required for the voice coil holder is now only 0.8 inches, which is much more reasonable. To avoid too tight a fit, the voice coil holder has therefore been designed to be 0.9 inches wide. The other dimensions for the voice coil holder are then set by the mechanial design of the rest of the actuator.

A picture of the voice coil is shown below:

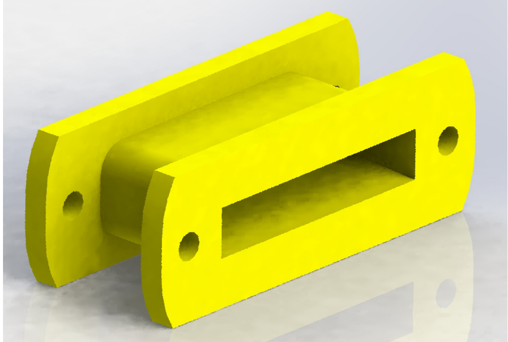


Figure 14: Picture of the voice coil around which the magnet wire will be wound

4.5 The Actuator Arm

To transmit the force acting on the voice coil, the voice coil is then mounted on an actuator arm as shown in the figures below:

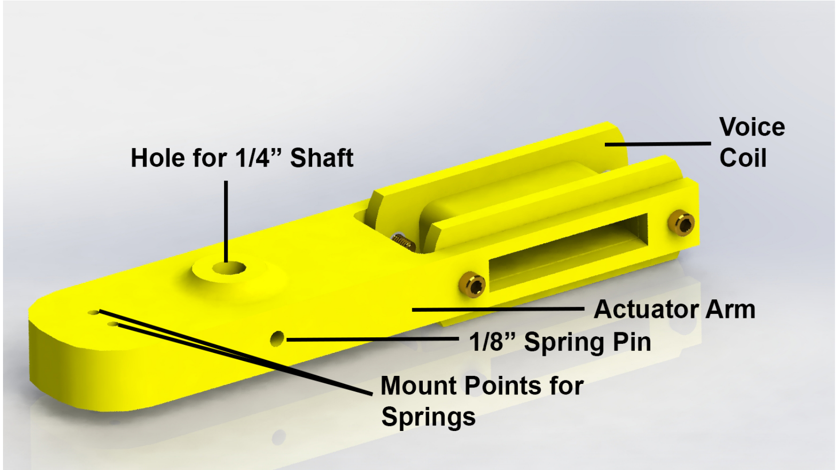
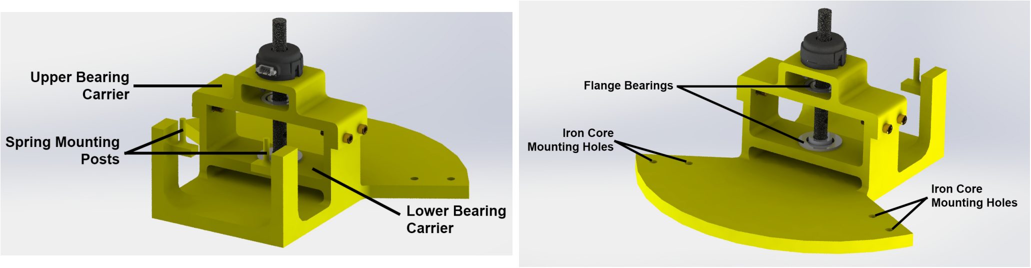


Figure 15: Picture of the actuator arm with the voice coil mounted to it.

In this configuration, the force acting on the voice coil will be transmitted along the actuator arm to the other end of the arm. In Figure 15, the other end of the arm contains two mount points for springs. In this prototype, the springs serve as the restoring force to allow the actuator arm to oscillate back and forth. However, when the actuator is installed on the actual robotic fish, the other end of the actuator arm will be connected to a tail section of the fish instead of springs in order to move that tail section. In addition, a 1/4in shaft is used as the pivot point for the actuator arm and the arm is pinned to the shaft using an 1/8in spring pin.

4.6 The Test Stand

Finally, the last major component of the actuator is the test stand. In the final actuator that will be installed on the robotic tuna, the test stand will be replaced by a proper waterproof housing that will contain the electronics and mechanical structure. However, for this prototype, it is a test stand as shown in the figures below:



(a) View from the back of the test stand (b) View from the front fo the test stand

Figure 16: Two different views of the test stand with labeled parts

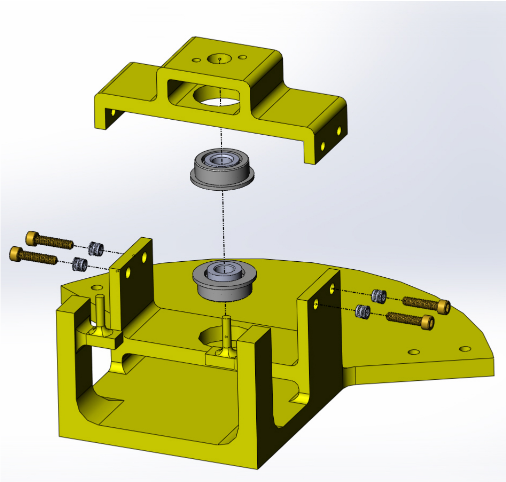


Figure 17: Exploded view of the test stand

As can be seen in the above figures, two flange bearings provide the support for the weight of the actuator arm with the voice coil attached to it. The test stand also provides mounting points for the springs that will provide the restoring force. The iron core then mounts on the front of the test stand. The key features of the test stand, as shown in Figures 16 and 17, are:

1. Mounting holes for 6-32 flat-head machine screws to mount the iron core to the test stand

2. Upper and lower flange bearings and bearing carriers to support the actuator arm. The upper bearing carrier is secured using four 4-40 socket head cap screws.

3. Spring mount points to mount springs that will provide the restoring force to allow the actuator arm to oscillate back and forth.

4.7 Electrical System and Data Collection

In addition to the mechanical design, in order for this prototype to actually function and be useful, it needs an electrical system and a way to collect data.

Given the mechanical design discussed above and the desired control scheme, the electrical system must be capable of delivering a current impulse to the voice coil at the point when the actuator arm is at the equilibrium position. To do this, the actuator must be able to:

1. Detect when the actuator arm is at the equilibrium position
2. Trigger a relatively large current impulse using a relatively low current and voltage signal

As such, although not fully designed, the electrical system consists of the following components:

1. A rotary encoder to detect the position of the actuator arm. For this prototype, we are using a US Digital E4T-250-250-S-H-D-2 rotary encoder.
2. A microcontroller such as an arduino or NI myRIO
3. A solid-state relay rated for at least a 12A throughput current
4. Power supply also rated for at least 12A of throughput current

With these components, the concept is that the rotary encoder will be mounted on top of the upper bearing carrier as shown in Figure 16. The rotary encoder can then provide position information. Using this information, velocity can be calculated in order to plot the velocity-position plot. This information can also be used by the microcontroller to detect when the arm is at the equilibrium position. The microcontroller can then emit a "True" voltage (typically a 5V signal) to the solid-state relay in order to trigger the current impulse required to generate a lorentz force acting on the voice coil. This system, however, has not been tested and future work will include testing this electrical system to determine its efficacy.

5 Conclusion and Future Work

In conclusion, the goal for research on the robotic tuna this semester was to design a more efficient propulsion system for the tail of the robotic tuna in order to achieve greater propulsion efficiency. By designing an actuator that relies on lorentz forces, we believe that the robotic tuna will be extremely efficient because it is able to harness natural phenomena such as resonance and vortex shedding in order to increase its propulsion efficiency substatially.

Although the actuator has been designed, it has not actually been prototyped or tested. As such, future work on this project will include prototyping and testing the design to determine its efficiency as well as force-generating capacity. The actuator then needs to be scaled down in size in order to be of appropriate size and weight to be used in the actual robotic fish.

6 Acknowledgments

This research would not have been possible without the help of several faculty members at Olin College. As such, I would like to express my heartfelt thanks and appreciation to the following people:

1. Professor David Barrett for his guidance and advice throughout this project as well as his help in manufacturing parts to build the prototype
2. Professor Rebecca Christianson who gave me the very quick refresher on magnetism and magnetic fields that I desperately needed
3. Professor Jose Oscar Mur-Miranda who taught me so much about efficient magnetic actuator design