Biomimetic Seal Flipper Rig Senior Project

Final Report

Project Sponsor: Dr. Graham Doig

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Authors:

Gordon Belyea

Laura Kawashiri

Dylan Rinker

Kurt Beske

Statement of Disclaimer:

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1 Introduction

The Biomimetic Seal Flipper Test Rig Project is a senior project sponsored by Dr. Graham Doig in the California Polytechnic State University's Aerospace Engineering Department (CPSU AERO) and executed by students within the College of Engineering's Mechanical Engineering Department (CPSU ME). Dr. Doig studies the hydrodynamics of seal flippers in his Fluids Laboratory for Interdisciplinary Projects (FLIP), located on the CPSU campus in San Luis Obispo, California. The research project began at the Taronga Zoo in Sydney, Australia, where Dr. Doig captured swimming footage of the world's only captive leopard seal, Casey. After Casey's death in 2014 [6], Dr. Doig has been in pursuit of a method for analyzing the propulsion generated by seal flipper motion for the development of non-rotary propellers. Biomimicry is "an approach to innovation that seeks sustainable solutions to human challenges by emulating nature's time-tested patterns and strategies" [9]. He wishes to use biomimicry to help optimize airfoils. Following his arrival at CPSU in the beginning of 2015, he has restored and experimented with the university's previously unused water channel. However, an appropriate mechanism for hydrofoil testing does not currently exist within the CPSU facilities, which has created the opportunity to work with ME undergraduate seniors. These four students are Gordon Belyea, Kurt Beske, Laura Kawashiri, and Dylan Rinker. Belyea, a fourth year, has project and job experience in testing, designing, and troubleshooting mechanical systems. Beske, a fifth year, has internship experience also towards mechanical design and testing. Kawashiri is a fourth year, pursuing a Biology minor, with knowledge of biomimetic design, manufacturing, and mechatronics. Rinker is a fourth year and an aspiring marine systems engineer, also with interests in biomimicry.

In order for the continuation of Dr. Doig's research, a testing rig was needed to allow for the simulation of seal flipper motion within a controlled environment. A modular design with great capacity for repeatability is necessary as Dr. Doig wishes to study various hydrofoil forms, linkages, and oscillation patterns. Each variation of flipper form and motion demands the ability to experiment with a broad range of settings, as well as run multiple tests with identical settings. As for the physical integrity of the device, the rig must have sufficient resistance to water and corrosion such as to ensure a lifetime of 3-5 years. In addition, for ease of maintenance, the hardware and materials within the assembly should be standardized and locally available.

This Final Design Report provides information of the design, testing, and use of the rig and has additions to the objectives, final design, design verification and coding sections. New sections include Product Realization and Conclusions and Recommendations.

1.1 Project Motivation

Biomimicry strives to implement the efficiency and sustainability of nature's systems, tested by evolution and natural selection, into human designs. Since the re-introduction of this concept in the early 1990's, designers from all fields have investigated the potential of biological organisms for optimization techniques. With respect to the field of hydrodynamics, aquatic and marine animals rely on the manipulation of fluid flow for survival. Because of this, propulsion vortices due to fish tail oscillations has been a popular topic of study since the time of Aristotle, with modern scientific research being conducted since the 1600s [5]. Given that fish tails only involve the sinusoidal oscillation of a single hydrofoil and that fish are generally easy to obtain for study, such experiments can be performed in water tunnels with relative ease. Analysis on more complicated flipper structures and oscillatory patterns, however, has experienced minimal research in comparison.

The project muse, Casey the leopard seal (*Hydrurga leptonyx*), belongs to the seal family (*Phocidae*) within the Order *Carnivora* [3]. Like most other true or earless seals, leopard seals feature a sleek, fusiform body and rely predominantly on the rear flippers to generate propulsion and front flippers for steering. Unlike fish or whales, seals have two separate rear flippers, evolved from ancestral hind legs that undulate left-to-right and are capable of expanding and contracting vertically and oscillating both in and out of phase. Using only these bodily deflections, these 9-12 foot long, 600-1000 pound animals can launch the entirety of their bodies past the surface [2]. Leopard seals, being notoriously vicious predators, demonstrate a level of speed and agility above the other members of their family. However, given the extreme and inconvenient nature of their native Antarctic habitat and the risk of attack, people have yet to obtain a thorough study of these creatures, much less analyze their biomechanics. Casey's status—a rescued, formerly-wild leopard seal—made him a rare organism of great value to the scientific community.

1.2 Water Tunnel Details

For the purpose of testing within university water tunnels, the majority of existing test rigs are custom-built for specific tunnels at given universities. Water tunnels are useful for researching complex flows in and vortex flow patterns are nearly identical for both wind and water tunnels [8]. However, the larger density of water allows for Reynolds numbers to be achieved with much lower velocity. This slower flow speed also improves visualization and imaging capacities and allows for more convenient force measurements.

The CPSU tunnel is a Rolling Hills Model 0710 and operates on a smaller scale with a test section comparable to a small fish tank, as shown in Figure 1 (see Table 1 for exact dimensions) [8]. The shell of the tunnel is fabricated out of steel and powder coated for corrosion protection. Its 6:1 contraction ratio produces a flow rate that can be controlled between 2 and 5 $^{in}/s$. The tunnel also comes with a honeycomb-patterned flow conditioner that straightens the streamlines before the water is passed into the test section to improve experimental accuracy and data collection capabilities.

To create the flow, water is drawn from the downstream end of the tunnel and pumped into the upstream end by a 1.5 hp centrifugal pump which runs on 115 V 60 Hz electricity. This creates a pressure differential that forces the fluid medium to flow. Seeing that it is plugged into the wall of the lab, we know that we can run whatever system we design off the wiring in this room if it is required.

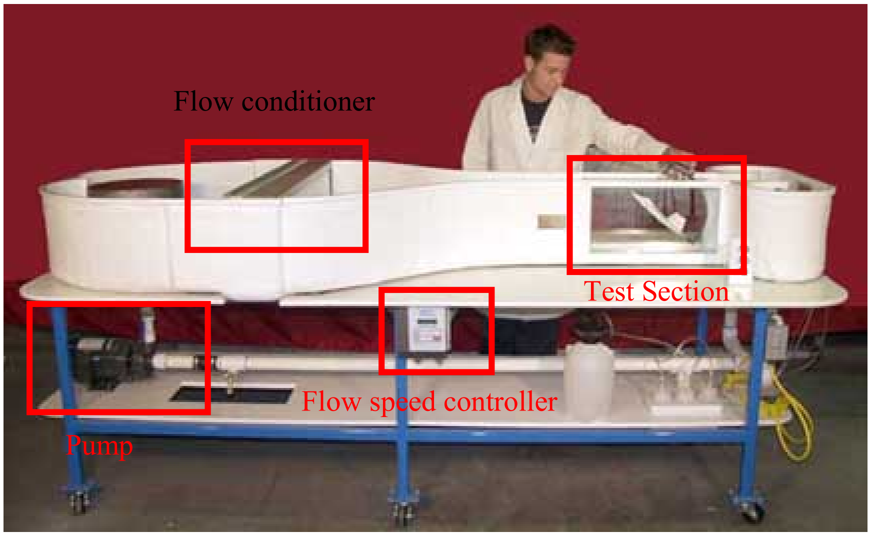


Figure 1. Rolling Hills Research Corporation Model 0710 University Desktop Water Channel [8].

1.3 Flow Observation and Imaging

Being able to accurately observe the flipper alignment and the effect on the fluid dynamics is paramount for our design to be useful. There are several ways to document the results of the future experiments. The most accurate method is the Particle Image Velocimetry (PIV) system in the lab. To operate the PIV, the water must be "seeded" with small particles [7]. A laser then fires two quick pulses into the fluid and the particles' position is captured with each one. Using the time between pulses and the distance each particle has traveled, the system is able to calculate the velocity field of a particular section. The model in our workspace is a Gemini 2000, built by New Wave Research. Since this is the most accurate way of determining the flow characteristics available to us and the tunnel is designed to be compatible with such a system, we will design our rig to allow for PIV use. Safety precautions will also have to be taken when working with a laser as powerful as this and must be taken into consideration when designing our rig.

Another method that comes with the water tunnel is the three color pressurized die system. This die is transferred via tubing from the die jars to wherever you would like to observe in the test section. The die moves along with the streamlines in the tunnel and offers a way to visualize the flow. Other water tunnel experiments have been successful using dies so the team is not eliminating this possibility.

1.4 Lab Space

We worked in the lab space shown in Figure 2. Its current state is not particularly conducive to organized work by four individuals, so once we are ready to start working with the tunnel we will have to do a bit of straightening-up. This photo also shows the area in which our rig must operate. There is some, albeit little, table space between the test section and computer to use, which will factor into our design choices.

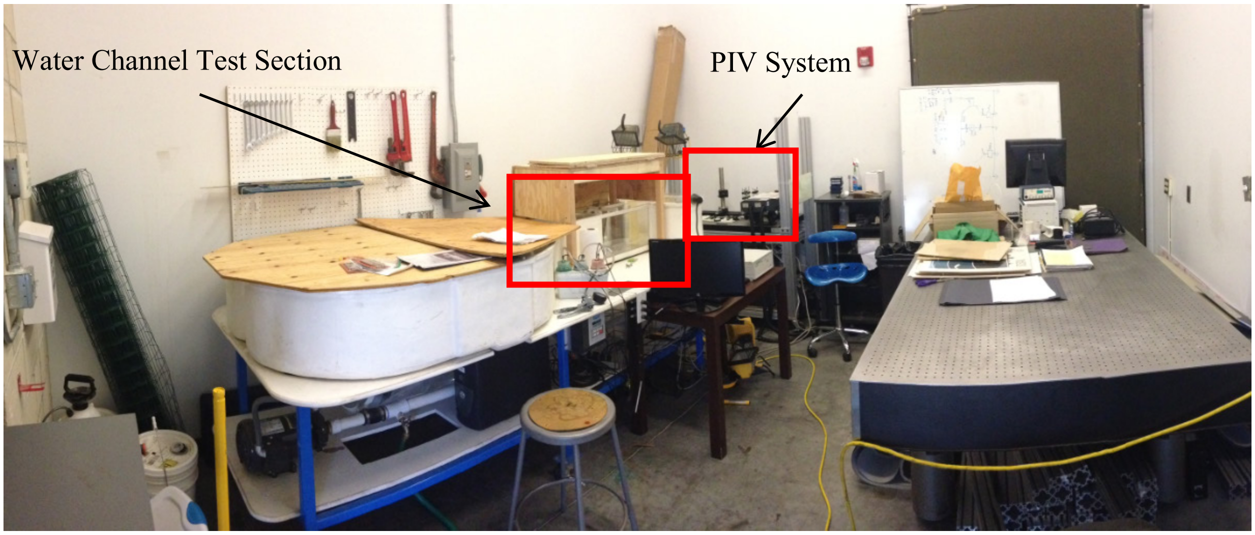


Figure 2. Lab space with water tunnel located in building 41 at Cal Poly, San Luis Obispo.

1.5 Existing Research and Similar Test Setups

While few of the published literary sources discuss the details surrounding the construction of the test equipment, the 2001 thesis paper by Ms. Catalina Lartiga from the University of Victoria on the development of a rig for kinetic turbine testing most closely resembles the project at hand. Unlike the CPSU water tunnel, the main device in Lartiga's thesis is a larger, stand-alone unit with a test section measuring 2.5 m in length with a 45 x 45 cm cross-section and maximum flow speed of 2 m/s [4] (pg. 11). The design of the rig, however, features a water-tight electromechanical interface, submerged rotating machinery, and a computer interface, which also describe the main requirements of this project. The final product of the Lartiga thesis, modeled in Figure 3, was an airtight lid-like attachment that fit atop the tunnel with a rotating plate in the center that supported the drive system for the downwards protruding rotor and shaft assembly.

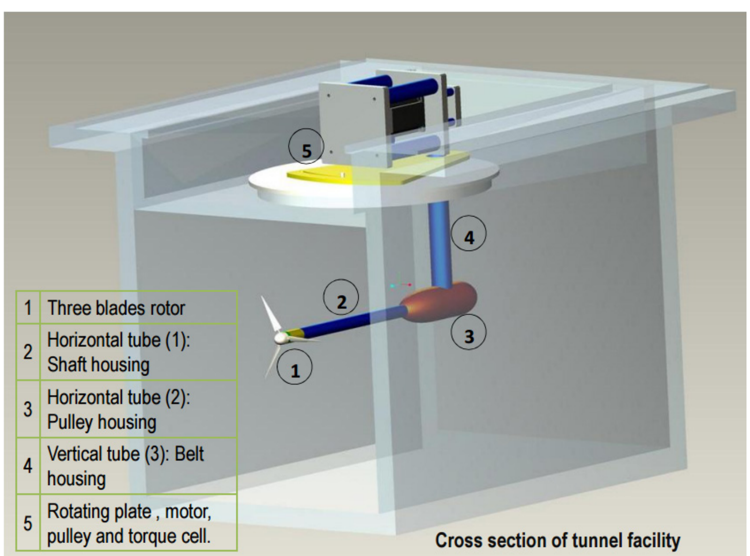


Figure 3. Lartiga Thesis Project Test Rig [4] (pg. 19).

Little can be found about research on dual hydrofoil propulsion methods with the foils alongside each other. However, researchers from the University of California, San Diego and Hobie Cat Co investigated the interaction between two hydrofoils in line to propel a kayak [10]. The hydrofoils swept back-and-forth across the centerline of the boat twisting through a 117° rotation in the process. The researchers were able to accurately model the forces that the foils experienced in their test run. Although this method of propulsion is different from the configuration that we will build, it was interesting to see that others have recently experimented with dual hydrofoils and found a way to describe the effect they had on one another using the Navier-Stokes equations for incompressible flow.

Another related arrangement was created with the same intention of studying tandem hydrofoils and is illustrated in the 2014 paper by Dewey et al [1]. Aside from the labels on Figure 4, however, little is mentioned about the construction or controls associated with the mechanism.

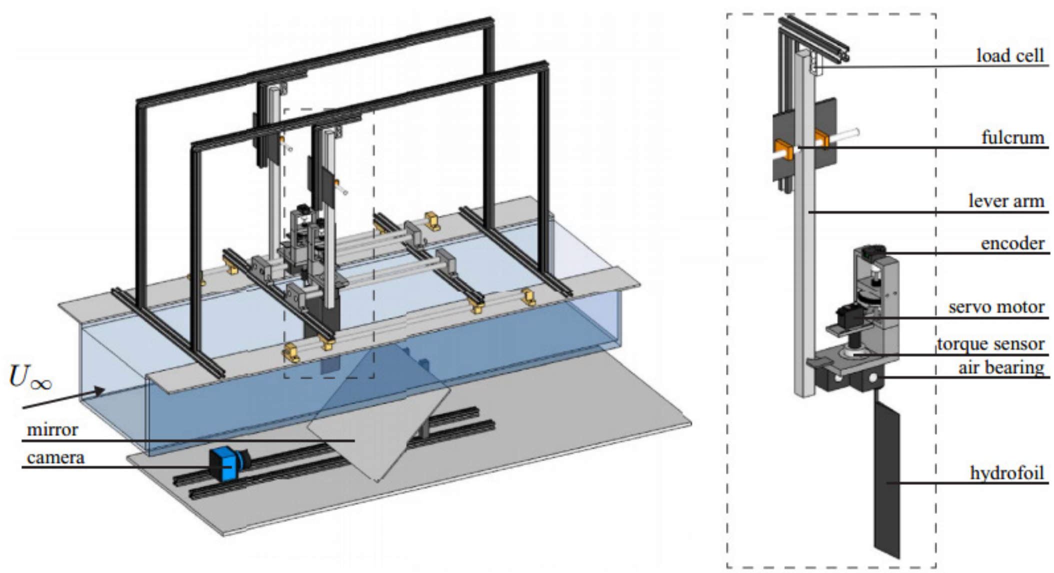


Figure 4. Dewey Research Experimental Setup [1] (pg. 3).

The flipper project combines a variety of fields and will require a vast set of skills. Research will have to be conducted past the field of mechanical engineering, reaching into biology, computer science, and electrical engineering as well. This should prove to be an exciting challenge that will contribute to the development toward a future in sustainable alternative propulsion methods.

2 Objectives

The goal of this project was to design and build a mechanical rig to perform the actuation of two simulated flippers for use in the water channel. Additionally, the rig must allow for visual analysis of the movement and hydrodynamics of biomimetic seal flippers within a water channel. To create a list of objectives, a quality function deployment (QFD) chart was used (Appendix A). This chart relates the needs of the customer to specific engineering requirements necessary to meet those needs. This tool was also used to determine the success of our final design in accomplishing Dr. Doig's requests. Table 1 was developed from the QFD chart and displays the engineering specifications as well as their tolerances and associated risks.

Table 1. Engineering Specifications

Spec. #	Parameter Description	Target/Requirement	Tolerance	Risk	Compliance
1	Test Section (L x W x H)	18" x 7.25" x 9.5"	Max.	L	I,A
2	Table Space Width	18.25"	Max.	L	I,A
3	Design Factor	1.5	±0.5	H	A
4	Electronics Protection	Yes	Max.	M	I
5	Power/Drivetrain	DC StepperMotor			
5A	Must have enough holding torque to keep flipper stationary in flow	.75 lb-in holding torque	Min	L	T, S
5B	Must provide capability to control flipper motion to 1°	Able to complete steps of <1°	Max	L	T, S
6	Production Cost	$1,000	Max.	L	A
7	Graphical User Interface/ Flipper Control				
7A	Must be coded in C to maintain compatibility with Arduino	Yes	Min	L	I
7B	Must operate from a terminal window or from a desktop application capable of running on Windows	Yes	Min	M	I
7C	Must be able to: control one or both flippers, set the frequency and range of each flipper, set the phase difference or delay between flippers, set the flippers at a desired location and leave stationary	Yes to all	Min	M	T
7D	The actual flipper angle must always be within 1° of input angle	Yes	Max	M	T
8	Standard Flipper Mount				
8A	Must be able to interface with any type of flipper, 3D printed or otherwise; no mechanical components such as keyways are allowed due to difficulty in manufacturing for end user	Yes	Min	M	I
8B	Must not interfere with the flow on or around the flipper control surfaces	Yes	Min	L	I
8C	Must not vibrate, rotate or fall off during operation	1in-lbf static torque without slipping, between 1 lbf and 10 lbf to remove	Min	L	T, I

8D	Must be able to change flippers repeatedly and achieve similar results each time	30 second change time, >5% angle difference between runs	Max	L	T, I
9	Variable horizontal distance between flippers	control distance between flippers to 1 mm	Min	M	I
10	Corrosion Resistance	5 years	Max.	M	S
11	Compatible with Laser Measurement System	Yes	Min.	L	I,S

Compliances: Analysis (A), Test (T), Similarity to Existing Designs (S), and Inspection (I)

Test Section Size: The testing device in question is a Rolling Hills Research Corporation Model 0710 University Desktop Water Tunnel. Given the fixed test section size, the flipper rig must fit within the test section measurements with room to account for boundary layer build up.

Table Width: The water tunnel is stationed on a table with minimal mobility and adjustability. All of the components of the rig must fit on top of the table.

Design Factor: An overall design factor of 1.5 is necessary to prolong the longevity of the rig as well as meeting various safety factors. It should be noted that minimal forces are applied to the rig due to the slow flow speed and small stagnation area.

Electronics Protection: Since the project deals heavily with water, the electronic components of the rig must be protected. This can be achieved by adding an electric casing or some type of water proofing or removing the electronic components from the water altogether. The auxiliary electronics equipment should also be housed together and protected for convenience and safety.

Power: Very little power is necessary for the movement of the flippers owning to the small current requirement and size of the motors. Having a rechargeable battery as a power source is preferable to using outlet power are there are already several pieces of equipment plugged in all around that room.

Production Cost: The project budget was flexible, as it was dependent on another project that Dr. Doig was sponsoring. He gave the project a number of $1,000 to work with.

User Interface: Dr. Doig requested an interface where he (or any other user) can adjust the position and motion of the flippers. The desired flipper control accuracy included 1° increments and a positional tolerance of $\pm 1°$. The user also had to be able to enable and disable each flipper, control their frequency and angular range, and control the phase difference of the flippers by integrating a lag or by other means. While a desktop application is ideal, a terminal window-based setup comprised of a list of parameter inputs was an acceptable and more achievable option.

Standard Mount: The rig will be used with flippers and hydrofoils of many shapes, sizes and methods of manufacturing. The most anticipated method of flipper production is 3D printing of plastic. Extensive modification or machining by the end user or flipper creator to be able to interface with the rig is not acceptable. The flippers must be able to be mounted and removed multiple times and have the experimental results be consistent for each run. This repeatability is paramount to the effectiveness of the rig. Since the purpose of this rig is to observe and collect data from very sensitive fluid flow over a hydrodynamic object, the mounting design may not interfere with the fluid flow on or around the flipper surface. No holes may be drilled or any protrusions attached to the flipper control surfaces. Also, the flipper must not rotate relative to the shaft it is attached to as the GUI control would be undermined and the data taken misleading. Finally, for the sake of user convenience, the mounting and positioning of the flipper should take less than 30 seconds.

Variable horizontal distance between flippers: Dr. Doig is also interested in experimenting with the distance between the flippers in the flow field. While this does not have to be an electronically or GUI controlled aspect of the project, the design must allow for the distance between the flippers to be adjusted in increments of 1mm. A system must be designed that will allow Dr. Doig to measure the distance between the flippers as well.

Corrosion Resistance: Our current target lifetime of the rig is about 5 years, and the most effective way to reach this goal is to make sure to use appropriate materials that will not easily corrode under contact with water. Marine-grade UHMD plastic is to be used for the base plate and motor planks. Aluminum and stainless steel are us

Laser Measurement System: The lab room where the water channel is located has a current laser measurement system set up. For ease of the project as well as our sponsor, we were requested to make our rig compatible with using the laser system as a means to visually analyze flow.

3 Initial Design Development

Through the first few weeks of our project, we began researching different aspects of our problem to build a strong foundation on which to base our solution. We have read the report [1] from a similar experiment testing dual hydrofoils performed by a university in Melbourne, Australia. We are hoping to gain insight into how they mounted their test rig and how the flippers were actuated. We are also looking into other tests in water channels so we can possibly glean some other ideas about working with water channels. More research will be required to determine the motion of the flippers and how out of phase they should rotate once we begin attempting to control our rig.

After we finished some preliminary research, idea generation was our next goal. We had three in-class idea generating activities to start to develop some of our ideas. After the ideation process, we realized that the best way to approach the final design concept was to break down the rig into subsystems. Each subsystem was addressed and analyzed separate of the other subsystems. This way we were able to pick and choose the best concepts for each subsystem and combine them to create the full rig.

3.1 Initial Ideation

The team used three separate ideation techniques to come up with a variety of feasible rig and subsystem components. The first idea was ideation through a morphological chart. Columns of major component titles were aligned on a wall and the team began sketching and putting up sticky notes of ideas underneath their respective columns. After that, the team used the 6-3-5 technique to come up with rough ideas of the entire rig. 6-3-5 entails six people given five minutes to draw three sketches. Since we only have a team of four, we deemed our technique the 4-3-5. Finally we used the concept of SCAMPER, which uses older similar concepts and compares them to what the team wants.

Since the preliminary design review, the team has made updates to the ideated designs below, which are discussed later in the report.

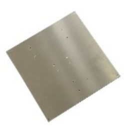
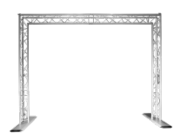
3.2 Comparative Analysis

The ideation process led the team to three main subsystems which will determine the main components of the build: The structure, the transmission, and the flipper mount. These subsystems do not encompass the electronic components since there was no ideation process needed to determine what was needed in that aspect. The three main subsystems were placed into weighted Pugh matrices to be compared and further narrow down potential concepts.

3.3 Structure

The Structure Pugh matrix, shown in Table 2, was used to help narrow down the overall supporting structure of the rig over the test section. Each idea was judged based on eight different criteria.

Table 2. Structure Pugh Matrix

						
Criteria	Weight	Flat Plate	Overhead Frame	Crossbeam	Indented Plate	Cantilevered Beam
Weight	2	D	-2	2	0	-2
Size	4	A	-4	4	0	-4
Ease of Attachment	3	T	0	-3	0	-3
Ease of Removal	3	U	0	0	0	-3
Durability	4	M	-4	-4	0	-4
Cost	1		-1	0	0	-1
Water Interference	5		5	0	-5	5
Sum			-6	-1	-5	-12

Weight, size, ease of attachment and removal, durability, safety, cost, and water interference were all vital criteria in deciding on the structural component. Weight and size are both related to how the structure fits over or in the test section, and how easy it is to remove from the water channel. Ease of attachment and removal describes how difficult it is to attach and remove other components from the structure itself. Durability is self-explanatory and vital towards keeping a corrosion resistant rig. Safety is always important for every build, which heavily ties in with weight. The cost of the structure itself is not too important since the bulk of the cost of this rig will be within other subsystems. Finally, water interference is the most important criteria of this subsystem, if the structure has potential to interfere with the flow of the water channel, all recorded data could be made null.

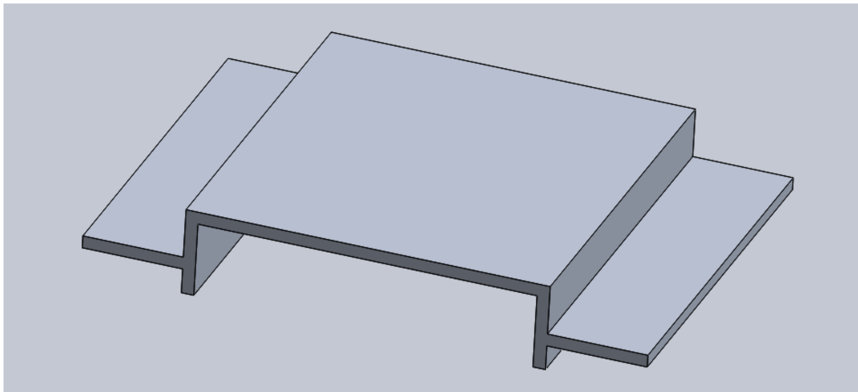


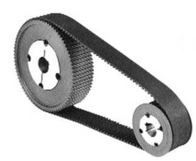
Figure 5. Flat plate conceptual design

The flat plate (figure 5) was selected as the datum of this matrix since the team believes it was the best possible selection for the structure subsystem. The flat plate as a datum, as well as each datum in the proceeding matrices, acts as a sum of zero. In the matrices, if the sum a component is negative, it is deemed worse than the datum, and if the sum is positive, it is considered a better selection than the datum. In the case of the structure, every concept added up to be negative, proving the flat plate to be the most effective structural concept. The crossbeam concept was the least negative in the matrix and, in general, not a bad idea. The main reason why a crossbeam across the test section is not feasible is its lack of enough surface area to attach other components to it. For example, as the design continues, the motor and electronics could be needed to mount directly to the structure, which is not possible with a simple crossbeam. The flat plate's lack of water interference and its simplicity of attachment to the test section as well as the ability to mount and attach components directly to the plate lead it to be an exceptional choice for the base structure of the rig.

3.4 Power Transmission

Since the rig itself will be powered with a DC motor, a transmission subsystem is necessary to increase precision in shaft movements as well as locate the flipper’s shafts. As shown in Table 3, three basic power transmission concepts were compared using six different criteria.

Table 3. Power Transmission Pugh Matrix

				
Criteria	Weight	Gears	Belts	Directly-Driven
Efficiency	1	-1	-1	D
Slippage	3	0	-3	A
Installation/Repair	4	4	4	T
Cost	3	-3	-3	U
Precision	5	5	5	M
Acquisition Difficulty	2	-2	-2	
Sum		3	0	

The three component concepts, gears, belts, and directly-driven shafts, had their efficiencies, slippage rates, time of installation and repair, cost rates, precision benefits, and acquisition difficulties compared. Efficiency, while important for all transmission systems, was not a major issue for the scope of this project since the flipper's movements are more about precision rather than raw speed or torque. Slippage was a necessary criterion since slippage within the transmission can lead to a much less precise shaft movement. The ease of installation and repair of the transmission system is needed for manufacturing purposes as well as actual use, especially with frequent flipper changes. The transmission cost can vary much more than the structure's costs can, hence the increased weight in this particular Pugh matrix. Precision, the most important criterion of this matrix, describes the minimum step amounts of the motor, which determines the rotational angle changes of each shaft. The difficulty of acquisition is noted in this matrix due to the necessity of properly locating the shafts; the transmission components have to be the correct size and properly gear up or down the motor. This is primarily a criterion to help prevent custom building transmission components such as gears.

Since a lack of power transmission, or a directly-driven shaft, is the simplest solution, the team selected it as the datum for the matrix. Neither the gears or belts were considered worse than the directly-driven shafts in the criteria comparison, but the gears came out on top with a sum of three. One characteristic of gears not analyzed in the matrix are their flexibility with material choices. Different material selection leads the team to a wider selection of gears overall, proving their acquisition difficulty to still be more difficult than a directly-driven shaft, but easier than a belt. The main issues with belts which led to their score of zero are their acquisition difficulty of specific sizes (especially timing belts), and their slippage rates, which can affect overall precision of the rig. Gears are the overall best selection for the transmission subsystem, primarily because of their increased angle precision through gearing down, as well as their ability to prevent damage to the motor by taking loads and torque that the motor would otherwise take.

3.5 Flipper Mount

Dr. Doig has requested the team to create a standard mount for each flipper, so that different flipper sizes and shapes may be traded out and tested with ease. Table 4 shows four different mount attachment components compared in a Pugh matrix using five weighted criteria.

Table 4. Flipper Mount Pugh Matrix

					
Criteria	Weight	Set Screw/Keyway	Pull Pin/Cotter Pin	Key Pin	Threaded Shaft/Flipper
Flow Interference	5	D	-5	0	0
Repeatability	5	A	0	0	-5
Ease of Use	3	T	-3	3	0
# of parts	1	U	-1	0	1
Manufacturability	4	M	4	-4	4
Sum			-5	-1	0

Many shaft securing and attachment methods already exist in industry, so the team selected four concepts which are most applicable to the project at hand. As table 4 shows, these four components were compared with criteria such as flow interference, repeatability and reusability, ease of use, number of parts, and manufacturability. As mentioned previously in the discussion of the structural subsystem, flow interference must not occur or the collected data could potentially be ruined. Repeatability and Ease of Use go hand-in-hand in a sense that the mount is easy to attach and remove without potential damage to the rig or large amounts of effort from the rig user. The number of parts is listed since many attachment methods have a number of small components which could be lost or dropped into the water channel. Manufacturability is most important in this particular subsystem since the mount will be directly attached or machined onto the shaft, which, for the team, could be a very large obstacle to get over.

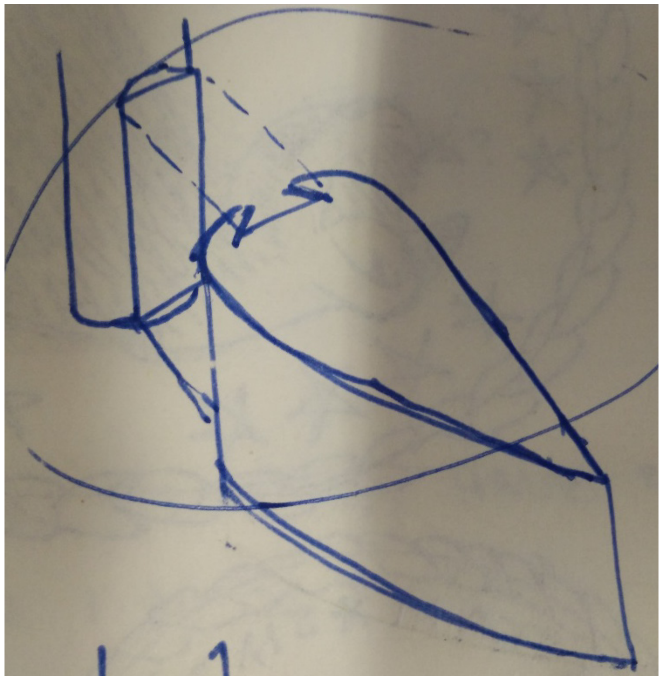


Figure 6. Keyway design for flipper attachment.

Similarly to the structure subsystem matrix, the keyway, similar to Figure 6, was chosen as the datum since the team believed it was the best possible choice as a mount. After going through each criteria's comparison, the threaded shaft came out with the highest score of zero, tied with the datum. Since the weighted Pugh matrix produced a tie between two concepts, the team had to make a decision between the two. We have decided to continue with our initial thoughts of the keyway. One problem of the threaded shaft not addressed in the Pugh matrix is the fact that the actual flippers will more than likely be 3D printed. Adding threads to 3D printed materials adds another variable into the overall modular and repeatable aspect of the rig, which ended up confirming our thoughts on using the keyway. The keyway and set screw mount will locate and secure the flipper with ease and with no real excess flow interference.

This keyway concept was later scrapped due to interference with the leading edge of the flipper. Newer conceptual and final design ideas relating to the flipper mount will be discussed in the next section.

3.6 Conceptual Design

After the preliminary design report and review, the team ran into problems regarding the flipper mount. Dr. Doig initially pointed out how a keyway on the shaft would disrupt the flow along the leading edge of the flipper, rendering the data collected useless. Besides the mount, the team has made small changes on the subsystems to streamline the rig.

3.6.1 Base Plate and Positioning Systems

While the overall shape of the base plate remains the same, slots have been added to account for a horizontal positioning system for what is referred to as the motor planks. The two motor planks are separate pieces from the overall plate that house and supporting the motor, driveshaft, and gears.

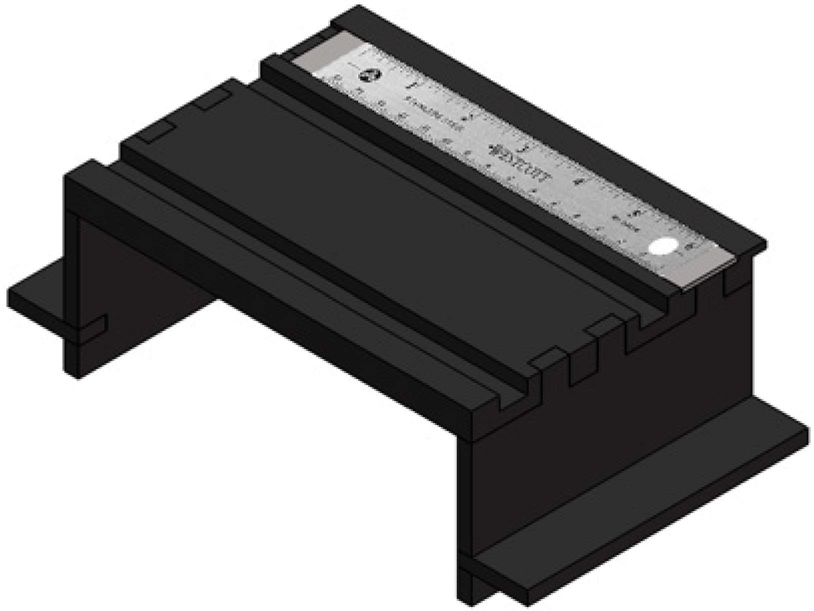


Figure 7. Motor Planks and Base Plate

As seen in Figure 7, a shallow indentation has been added half an inch from the back of the plate. This is to make room for the addition of a 6-inch stainless steel ruler, such that measuring the distance between the two flippers comes with ease. Gauge slots have also been cut into the planks to act as visual locators for this reason. Over each slot is a piece of clear plastic tape with a permanent line drawn in the center of each slot. This allows the user to interpret the measurement more accurately than with the slot alone. Each plank can be clamped down during operation or transport using a simple binder clip. During operation, it is not necessary to have the planks clamped as the slots on the planks provide enough stability.

The flipper-side of the new motor planks has two holes (See Figure 8), one for the flipper shaft and one for the positioning tool. In order to achieve repeatability for each experiment, the flippers must be positioned in an accurate and easy manner every time. The locating tool offers a solution to this problem, which will be discussed further in the final design section.

Figure 8. Motor Plank with Locating Tool

3.6.2 Power Transmission

After choosing gears as the preferred of power transmission, the team decided on using miter gears rather than spur gears. This reduces the number of bearings and shafts necessary by allowing the motor to be positioned horizontally, cleaning a more efficient design. The motor, shafts, and gears are extrapolated upon in the final design section.

3.6.3 Flipper Mount

The method of attaching the flipper to the driven shaft proved to be one of the most difficult design items of the project. The attachment method has to support fast installation and removal, be able to use several different kinds of flippers and change them easily, the flipper must not move on the shaft during use, it must not interfere with the flow characteristics during testing, it must be waterproof, the flipper must be located accurately upon installation and the installation process must not require any machining. While all of the specifications are necessary for the rig to be user-friendly and produce good results, they eliminated the possibility of using set screws, machined shafts or clamps. During one of our classes, several other teams and our advisor, Professor Sarah Harding, attempted to help us come up with an idea but none proved to be feasible. The team had several other brainstorming sessions to solve this issue.

The first and second concepts both used friction against a rubbery material to support the shaft. The first concept, which never went into testing, was the idea of using rubber O-rings and an interference fit to support the flipper. The idea was to machine two slots into the shaft to house the two O-rings, which would be pressed into a hole in the flipper. Figure 9 shows this concept. This idea never went into testing due to its impracticality with machining, and the likelihood of such small O-rings getting lost or stuck inside the hole.

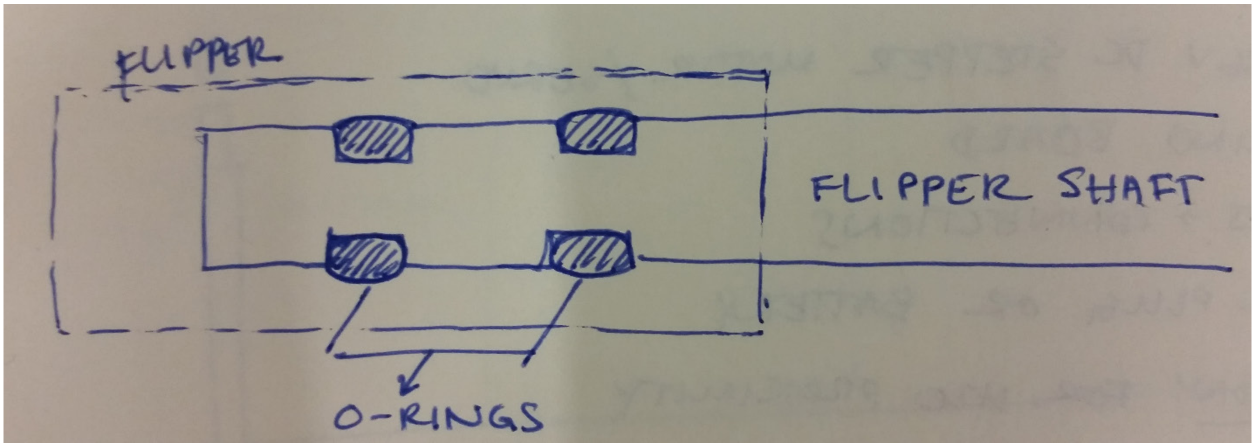


Figure 9. Sketch of O-Ring Flipper Mount Idea

The team then came across a similar idea, still using friction between the flipper and a rubbery substance the support the shaft. This time around, the shaft would be evenly plasti-dipped and then inserted into a hole in the flipper in an interference fit. After testing plasti-dipped shafts of various sizes with various plasti-dipped thickness, the team decided it was overall too unreliable to be effective. The plasti-dip would rarely set evenly, and tended to shred when inserted into the flipper. The plasti-dip vertically supported the flipper, but allowed for the flipper to spin almost freely on the shaft. Figures 10 and 11 show an example of the plasti-dipped shafts used for testing. The initial test plan was to attach a force gauge to the end of a mocked-up flipper attached to the plasti-dipped shaft, and see how much torque was required to spin the flipper on the shaft. Unfortunately, it was so obvious that the plasti-dip would not hold the flipper in place that the test was not necessary.

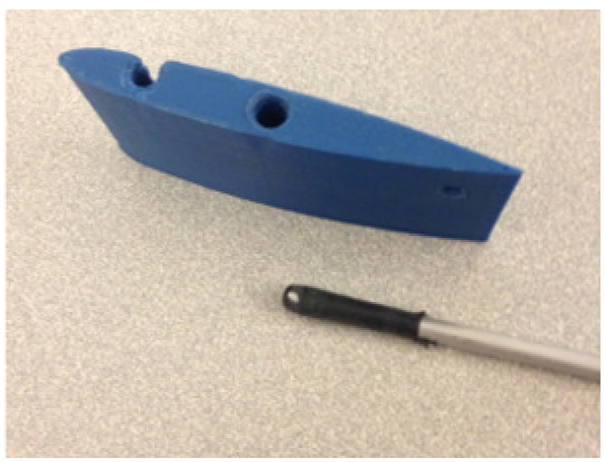


Figure 10. Plasti-dipped Shaft and Mock-up Flipper

Figure 11. Plasti-dip damage after repeated installation

After the failure of the past concepts, the team finally landed on the final conceptual design for the flipper mount. Each new flipper is permanently secured on a pre-cut shaft.

3.7 Analysis

The team performed preliminary flow analysis of the boundary layer based on the maximum speed of the water channel. The maximum Reynolds Number is 312.1. The boundary later is expected to be no greater than 0.195 in at the halfway point of the flipper and 0.39 in at trailing end of the flipper.

The team also calculated the forces and moments on the flipper and its connecting shaft caused by the flowing water in the channel. I was determined that the worst-case load will occur with the chord of the flipper oriented perpendicular to the flow. This will cause a shear stress in the flipper shaft normal to its length as well as bending moments causing the shaft to bend and twist. The team chose a flipper size of 3"x5" and modeled it as a flat plate to give an even more conservative value. A free body diagram of the case described above is shown in Figure 12.

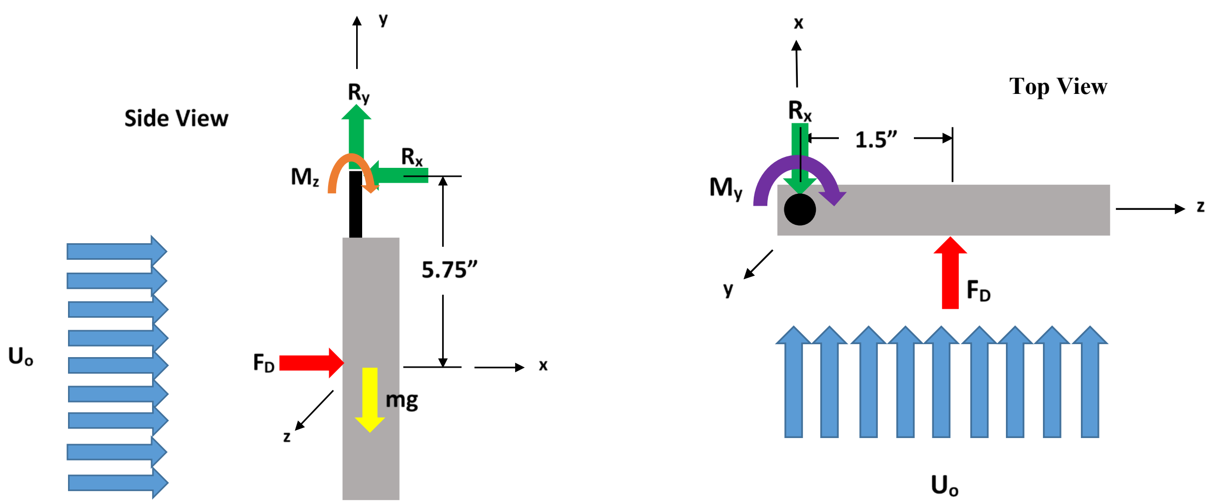


Figure 12. Free body diagram of flipper oriented perpendicular to flow.

The equation used to calculate the force on the flipper, F_D, is derived from Bernoulli's equation for inviscid and incompressible flow. This equation is modified by an experimentally derived drag coefficient that is shape dependent. The drag coefficient chosen for this analysis was 1.9, a value given in

Fundamentals of Fluids Mechanics [11] for a rectangular bluff body with a height-to-depth ratio of 0.1 or less. In actuality, the drag coefficient of the real flipper will be less than this value, making this a conservative estimate for the forces. Bernoulli's equation equates the total head of water and any two points in an incompressible flow and the upstream location and flipper location were chosen. The governing equation for our system is shown in Equation 1.

$$\left[p_o + \frac{u^2\rho}{2} + \rho g z\right]_{free-stream} = \left[p_o + \frac{u^2\rho}{2} + \rho g z\right]_{flipper}$$

Equation 1. Bernoulli's equation adapted to the flipper in water tunnel flow

Canceling the velocity term at the flipper and elevation variation, the velocity term of the free-stream equates to the stagnation pressure on the flipper. This equation is modified by the aforementioned drag coefficient and multiplied by the flipper face area to give the equation for the drag force shown in Equation 2.

$$F_D = \frac{1}{2}\rho U^2 C_D A$$

Equation 2. Drag force on flipper caused by flow in water tunnel.

In order to calculate reasonable forces, the team had to make a few assumptions about the size of the flipper. A size of 3"x5" was chosen because when oriented perpendicular to the flow, it would span 80% of the width of the tunnel and cover 43.6% of the total tunnel cross section. The team does not predict any flippers larger than this will be used for this rig. The distance from the shaft bearing to the equivalent point of action in the center of the flipper is estimated to be 5.75 inches. This locates the flipper center in the middle of the flow field with an inch between the surface of the water and the bottom of our support. Table 5 shows the flow characteristics as well as the flipper dimensions. The forces and moments were calculated using the static analysis shown in Appendix C. The results of the calculations are shown in Table 6.

Table 5. Flow and Flipper Characteristics for Force Calculation

Water density	1.940	slugs/ft^3
Downstream Velocity	5.00	in/s
Downstream Velocity	0.417	ft/s
Drag Coefficient	1.900	[-]
Flipper Width	3.000	In
Flipper Length	5.000	In
Distance from flipper center to shaft bearing	5.750	In

Table 6. Force and Moment Calculation Results (See Figure 5 for graphical representation)

F_D=	0.033	lbf	force along stream
M_z=	0.008	ft-lbf	shaft bending moment
M_y=	0.004	ft-lbf	shaft rotation moment

These forces will be used to perform stress calculations in order to select the material and size for our shafts to ensure they will not fail. At this point, a design factor will be agreed upon to make our system even more robust. It is also important to note that the total force in the flow direction on our entire system will be twice that of the force on each flipper given that the drag force in Equation 2 is directly proportional to the area. The total force in this direction 0.066 lbf. The team is confident that this force will be overcome by the friction between our apparatus and the walls of the water channel. The shaft rotation moment from this calculation must be exceeded by the holding torque capable of our motors.

4 Final Design

Our final design consists of ideas generated from the preliminary design report as well as the updates mentioned previously. This section will discuss the final design in detail, additional analysis to aid the design, component selection, electronics, and finally, safety and repair.

4.1 Detailed Design Description

The rig's design can be broken down into five main subsystems, the base plate, the motor planks and transmission, the flipper mount, and the electronics. The final design is shown below in Figures 13 and 14.

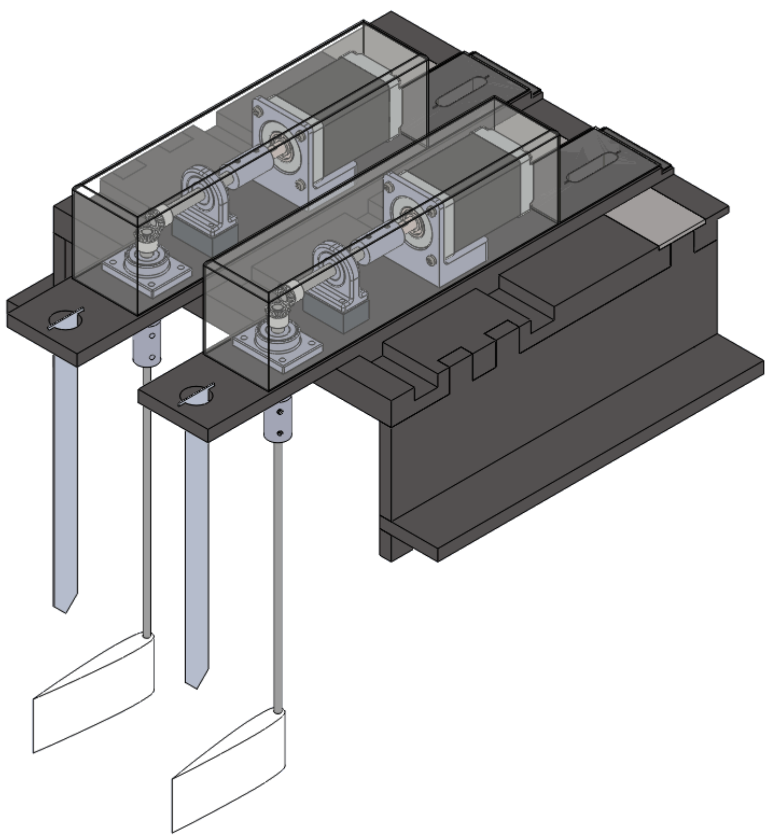


Figure 13. Final design model.

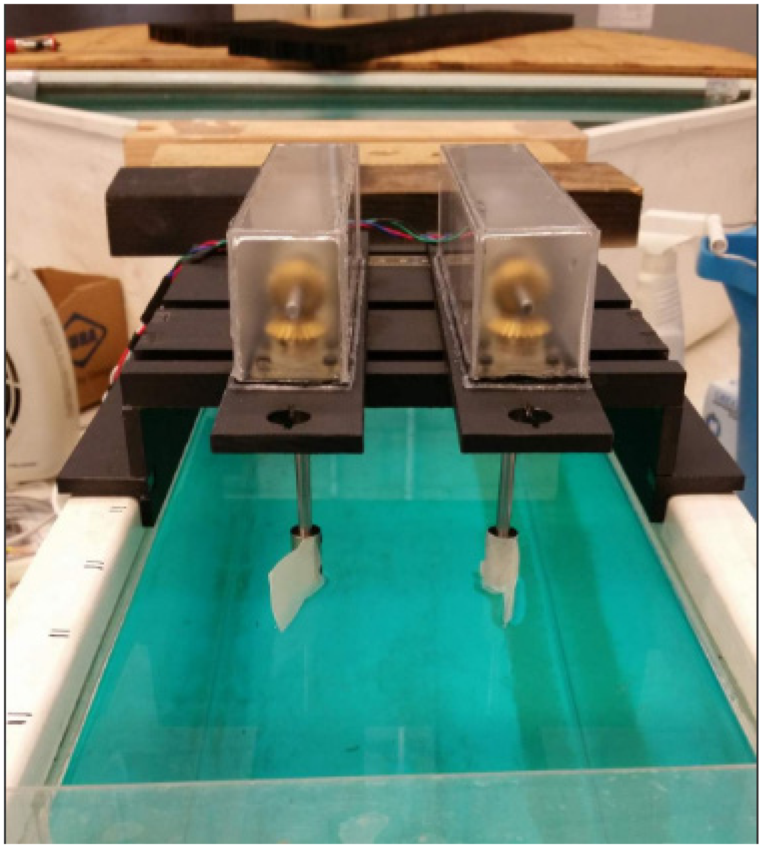


Figure 14. Final assembly in the water channel.

4.1.1 Base Plate and Motor Planks

The base plate design, described in section 4.6.1 was fabricated from High density polyethylene (HDPE) plastic. It is comprised of five separate pieces of HDPE: the two vertical plates, two flanges and the single horizontal center plank. The horizontal section of the base plate is 1/2-inch-thick while the supports and flanges needed to raise the rig above the water channel level will be made 1/4 inch thick. This material allows the operator to move the motor planks without any mechanical assistance.

The vertical supports and the center plank are connected using a square dovetail joint. The dovetails intersect with epoxy binding the two pieces of HDPE. This technique eliminates the need for fasteners or a welding process. It is be strong, durable and aesthetically pleasing. The flanges will be joined to the vertical supports in a similar fashion. The center of the flanges are notched in the center with protrusions on each end. The vertical supports are notched on the vertical edge with the height equal to the thickness of the flange and the depth equal to the width of the flange edges. See Figure 15**.** for reference. Drawings CPS101A and B in Appendix F provide dimensions.

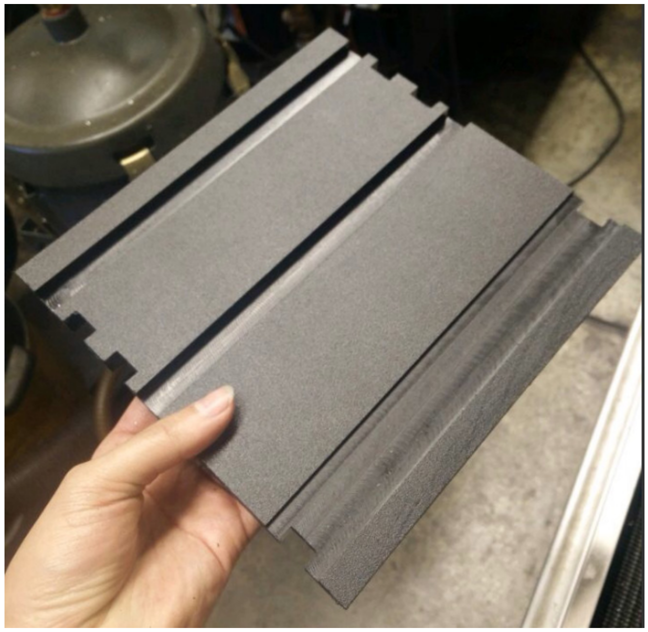


Figure 15. Base plate with machined grooves and dovetail joints.

The motor planks carrying the power transmission were also fabricated from 0.25 inch HDPE plastic. They are 1.5 inches wide to accommodate the motor mounting. Protrusions of 0.25 inch HDPE glued to the bottom of each plank match the base plate grooves, allowing the planks to slide horizontally across the width of the water channel.

The grooves in the horizontal plate were carefully designed to allow the motor planks to slide and be removed but creates enough friction to keep the planks from moving incidentally or falling out entirely.

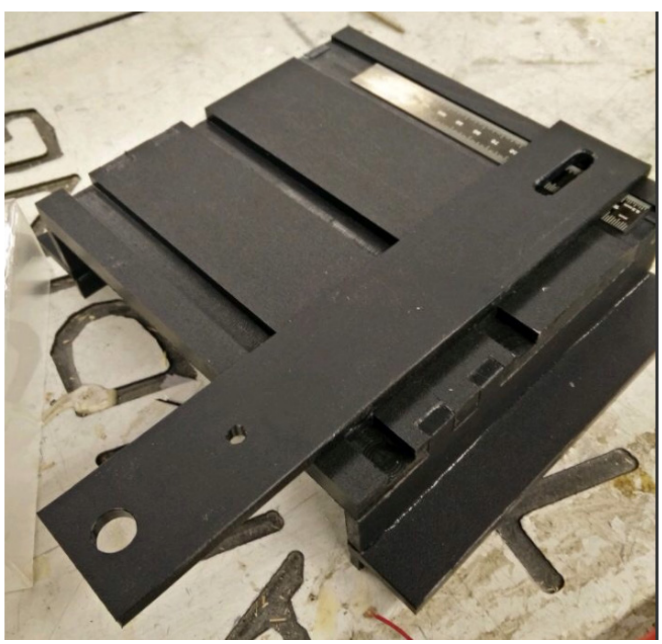


Figure 16. Fully-assembled base plate with supports after being epoxied. The ruler had not yet been epoxied onto the rig. The motor planks have holes drilled for the vertical shaft and positioning tool.

4.1.2 Power Transmission

The rotation of the horizontally-mounted stepper motor is transferred from a horizontal shaft to a vertical shaft via 90° miter gears. These gears are made out of brass and include a set screw to secure it on the shaft. They have the same diameter and number of teeth so the gear ratio is unity. The horizontal shaft is supported by a ball bearing housed in a custom designed 3D printed bearing carrier. These keep the shafts aligned and will ensure complete gear tooth engagement. See drawing CPS214 for reference. This carrier has been designed with four holes through which screws secure it to the plank. This bearing ensures that the rotational motion of the motor will transfer efficiently to the driven shaft.

The driven shaft is supported by the same type of ball bearings as the horizontal shaft, also housed in 3D printed bearing carriers in a different configuration. A pair of these carriers is shown in Figure 17**.** See drawing CPS212 for dimensions. However, in this case, the shaft is supported by bearings above and below the motor plank. Since these are concentric, bolts have been used to sandwich the plank between the bearing carriers. The gear of the driven shaft is constrained from moving vertically by the bearing carrier on top of the plank and by the driving gear.

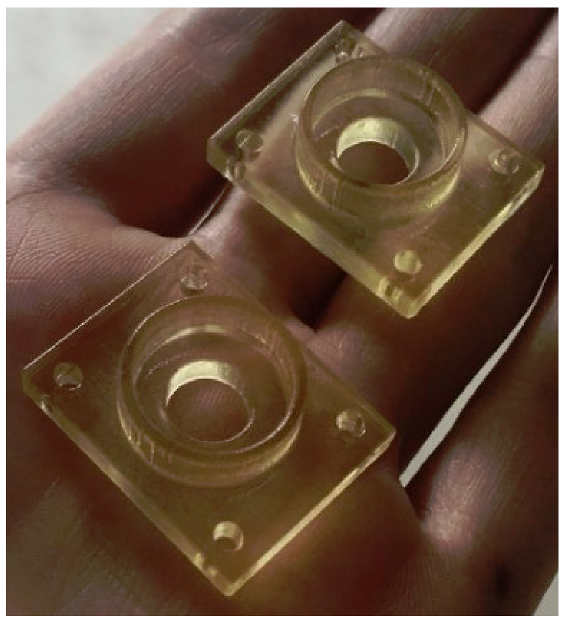


Figure 17. Vertical shaft supports made using 3D printed resign cured with UV light.

4.1.3 Flipper Attachment

Each flipper has its own shaft for the duration of its use. The flippers are made with a 3 mm hole in which a 3 mm shaft will be epoxied. A large quantity of these 3 mm shafts have been pre-cut by the team and epoxy has been purchased. The user will install a new shaft in every flipper he or she chooses to use. While this does take some effort and time by the user, no additional machining is required, the flipper will be secure and once the shaft has been epoxied in, it can be used as many times as is desired without further modification.

The flipper shaft is then connected to the driving shaft via a concentric shaft coupler and secured with a set screw. When installing the flipper shaft, the user will use the locating tool to position the flipper before tightening the set screw.

The coupling method is much stronger and durable than attempting to use friction alone to keep the flipper from rotating on its shaft. It also is not labor intensive for the user and no machining of the flipper will be required except for a 3 mm hole on the top.

This method allows for flipper repeatability, as the control surface and edges are not affected by repeated installation and removal. This method of attachment also does not affect the flow around the flipper and provides good visibility for the PIV system.

4.1.4 Electronics

The electronic subsystem consists of a 2s LiPo battery, a 5-volt voltage regulator, an Arduino and Arduino stepper motor shield, and two NEMA 11 stepper motors. These motors are rated at a torque of 9.5 N-cm, drawing 670 mA per phase at 4.6 volts. The motors are mounted with a mounting plate onto the motor planks, while the rest of the electronic components are located in a project box which can be set next to the water channel. This box helps reduce the risk of splashing onto the electronics and shorting out the rig. The electronic components, minus the motors, can be visualized in the wiring diagram in a later section of this report.

The battery powers both motors, transmitting consistent voltage via the voltage regulator. The Arduino is powered by and receives commands from the computer via USB.

4.2 Shaft Stress and Deflection Calculations

Once the static forces on the flipper for a worst-case scenario were calculated, the shafts were able to be sized accordingly. While adequate shaft size was never a concern, it is important to validate this hypothesis with analysis.

A calculation was performed using a flipper shaft diameter of 5 mm, or 0.195 in. See Appendix E. This shaft is assumed at this point to be 6061-T6 aluminum, which will resist corrosion better than a steel shaft over time. For these calculations, the drag force on the shaft itself is assumed to be negligible. The drag force from the flipper is assumed to be applied in the center of the flipper and the lengths used to calculate moments are based on this assumption. Tables 7 and 8 the parameters used to calculate the stress and deflections of the shaft and the resulting values.

Table 7. Shaft Dimensions and Material Properties for Bending/Torsion Analysis of Stainless Steel

Shaft Deflection/ Torsion Parameters - Stainless Steel		
Shaft diameter	5	mm
Shaft diameter	0.195	in
Shaft radius	2.5	mm
Shaft radius	0.0975	in
Distance from flipper center to shaft bearing	3	in
Tensile strength (yield)	31200	psi
Shaft modulus of elasticity (E)	293000000	psi
Shaft modulus of rigidity (G)	11200000	psi
Design Factor	1.5	

Table 8. Shaft Bending Stress and Strain, Torsional Strain Values for Stainless Steel

Bending Stress, Deflection and Torsion			
σ=	197.4	Psi	Maximum bending stress
FOS bending=	158		Factor of Safety against bending yield
δ=	2E-05	in	Flipper deflection from bending
θ=	0.0081	Degrees	Flipper torsional deflection

Table 9. Shaft Dimensions and Material Properties for Bending/Torsion Analysis of Brass

Shaft Deflection/ Torsion Parameters - Brass		
Shaft diameter	3	mm
Shaft diameter	0.117	in
Shaft radius	1.5	mm
Shaft radius	0.0585	in
Distance from flipper center to shaft coupling	5	in
Tensile strength (yield)	19600	psi
Shaft modulus of elasticity (E)	15200000	psi
Shaft modulus of rigidity (G)	5800000	psi
Design Factor	1.5	

Table 10. Shaft Bending Stress and Strain, Torsional Strain Values for Brass

Bending Stress, Deflection and Torsion			
σ=	914.1	Psi	Maximum bending stress
FOS bending=	21.44		Factor of Safety against bending yield
δ=	0.009	in	Flipper deflection from bending
θ=	0.3918	Degrees	Flipper torsional deflection

This analysis proves that both the 5 mm and 3 mm shafts will be sufficient for our design. The calculations show a factor of safety of over 21 for shaft bending yield with a maximum stress of 915 psi including the design factor of 1.5. The 0.01 inches of flipper deflection in the downstream direction is insignificant.

4.3 Cost Analysis

Dr. Doig budgeted about $1000 for the entire cost of our project and the final cost totaled $620. For a full cost breakdown, refer to the BOM (Appendix E). The major costs associated with the test rig stem from 2 subsystems: the electronics and the motor mounts. The electronics contributed to the majority of the cost of the project. Within this subsystem there is the battery, voltage regulator, Arduino and stepper motor shield, among others. The remaining components and hardware were not significant expenses compared to the electronics. The group was able to use available resources supplied by the Cal Poly machine shops and some that the team previously owned to avoid purchasing unnecessary items.

4.4 Material and Component Selection

The two biggest factors involved in material selection were water resistance and corrosion, which go hand in hand.

4.4.1 Base Plate and Motor Plank Materials

Since we planned on sliding the motor planks along the base plate to account for lateral positioning, a slippery, water resistance, and stiff material was needed. The team has selected marine grade HDPE (High Density Polyethylene) for these components.

HDPE has a very low coefficient of friction with itself (0.2-0.3 for static and kinetic), which is beneficial because it allows the motor planks to slide along the base plate to horizontally position the flippers with ease. HDPE is also very durable, cheap, and most importantly, water resistant. The type of HDPE the team chose is commonly found in applications for boats.

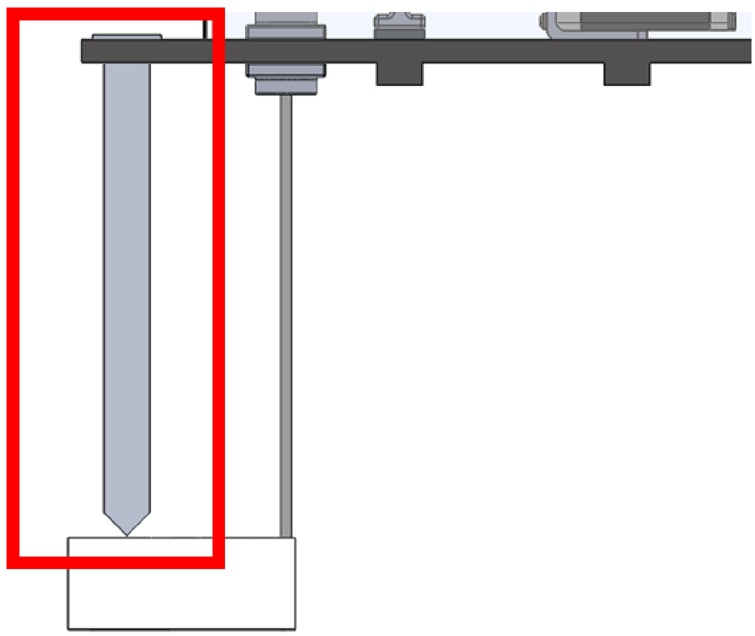


Figure 18. Positioning tool, side view

The flipper locating tool (Figures 18 and 19) is a piece of laser cut acrylic plastic. See Figure 20 for reference.

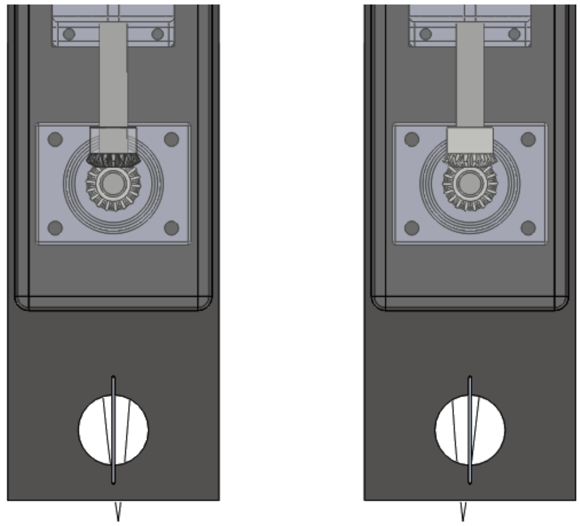


Figure 19. Top view of Positioning tool used to locate the flippers (shown as off center for emphasis)

Figure 20. Positioning tools after machining. The black spots are areas that the laser burned. They do not affect the operation of the positioning tools and actually provide a better visual guide to line up the flipper.

4.4.2 Motor, Shafts, and Gears

Dr. Doig requested a flipper angle change accuracy of ±1°. After looking through various servos and gears, the team decided on using a bipolar stepper motor.

The initial plan was to use a simple servo motor and gear it down to achieve accurate movements. This idea was scrapped due to servo motors constrained movement (180°), and the lack of plentiful gear sizes with such small bore diameters. We have selected a NEMA 11 stepper motor for our power, which has a

5 mm driveshaft, so in turn, the horizontal shaft will be 5 mm as well. These two shafts are coupled with an aluminum flex coupler. This motor moves at 1.8° per step, and can run at half steps, which is all we need for our accuracy constraints. The horizontal and vertical out-of-water shafts will be, like mentioned earlier, 5 mm, and steel. The vertical, underwater flipper shaft will be brass and 1/8 inch coupled to the 5 mm shaft using a stainless steel coupler. The smaller diameter of the shaft is to account for potentially small flipper sizes. Each shaft are supported by single row deep groove ball bearings, which are housed in a 3D-printed, plastic housing mounted to the motor planks with a dovetail slot for the driveshaft bearing, and steel screws for the flipper shaft bearing. These bearings can be found in Figure 21.

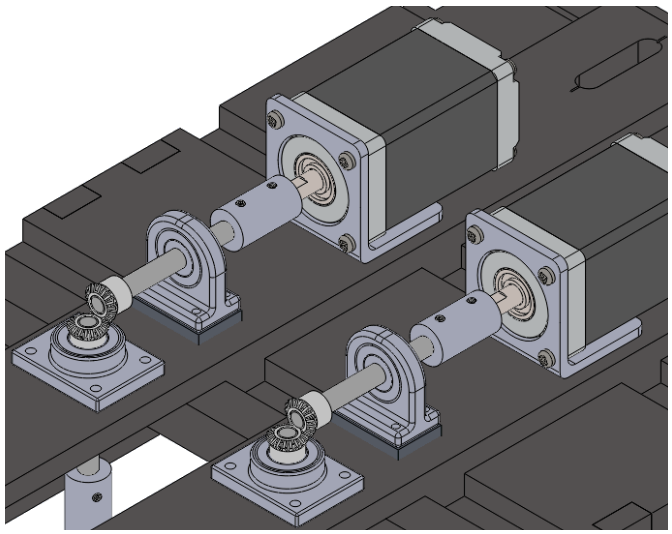


Figure 21. Drivetrain with bearing supports and bearings

As was previously discussed, the gears are brass. Since the stepper motor is capable of "stepping down," a gear ratio of 1:1 is all that is needed.

To add additional water resistance, the motors, drive shafts, and gears are protected in a transparent housing. This housing was made by epoxying together professionally-cut rectangular pieces of acrylic. The surface of the housing that rests on the motor planks is coated with RTV silicon adhesive sealant. This provides a water-tight seal around the mechanical components. This prevents water from coming into contact in the event of splashing but does not prevent exposure if the plank were to be dropped in the channel.

4.4.3 Electronics

After much deliberation between the team, we have settled on using an Arduino to control the motors. An Arduino stepper motor shield was added for ease of coding and control. The Arduino was selected over the Raspberry Pi due to the plethora of information about it online as well as its ease of use. The team would have settled for the more versatile Raspberry Pi if it weren't for the fact that it can only run on a Linux operating system, which breaks the constraints given to the team by Dr. Doig.

The motors are powered with a 2s LiPo battery run through a 5 volt, 3 Amp regulator. The regulator is necessary to ensure consistent voltage to be supplied to the motor to maintain consistent motor steps, and in turn, consistent flipper accuracy. The current is limited to 3 amps so as to not overload the motors and potentially break them.

The Arduino, power supply, and wiring are contained in a project box which will help protect them from potential splashing as well as make the rig a little more aesthetically pleasing. A switch was added in series with the motor cables allowing for quick shut off and start up.

4.5 Coding Flowchart and Wiring Diagram

The device is run using an Arduino UNO microcontroller with an Adafruit v2.3 stepper motor shield. The microcontroller is powered through the computer via USB while the motors are powered by a 7.4V lithium polymer battery. The battery power passes through a voltage regulator before connecting to the Arduino and shield, which then controls both of the NEMA 11 bipolar stepper motors. Figure 22 provides the schematic for the wiring and placement of the electronic components of the rig.

The code employs C++ and the object-oriented programming model, such that it controls an object by defining it with a series of controllable parameters, as opposed to the traditional action-based coding logic. In this case, the flipper constitutes the object to be controlled and contains the following user-defined parameters: a name, an ENABLE flag, a range of motion, a frequency, a connection port number, and a step style. The user can adjust these parameters by opening a serial monitor using the software provided by Arduino and sending commands. A command is given by typing a string of characters into the command box within the serial monitor window, which the program reads in and parses to determine the significance of each character. In order to execute the instruction, each character is associated with a specific aspect of a parameter. A typical command would appear as follows:

```
1R 60
```

The first character indicates which of the two flippers to control, the second corresponds to the parameter, and the following characters represent the new value of the parameter. The command above, therefore, translates to "change Flipper 1's range of motion to 60 degrees". Once the program deconstructs the string to understand the individual characters, it can run the appropriate functions to make the appropriate changes. Explicit instructions for commanding the device are contained in the operation manual created for this project. Ideally, the user would interact with a graphical user interface (GUI) in order to send these commands.

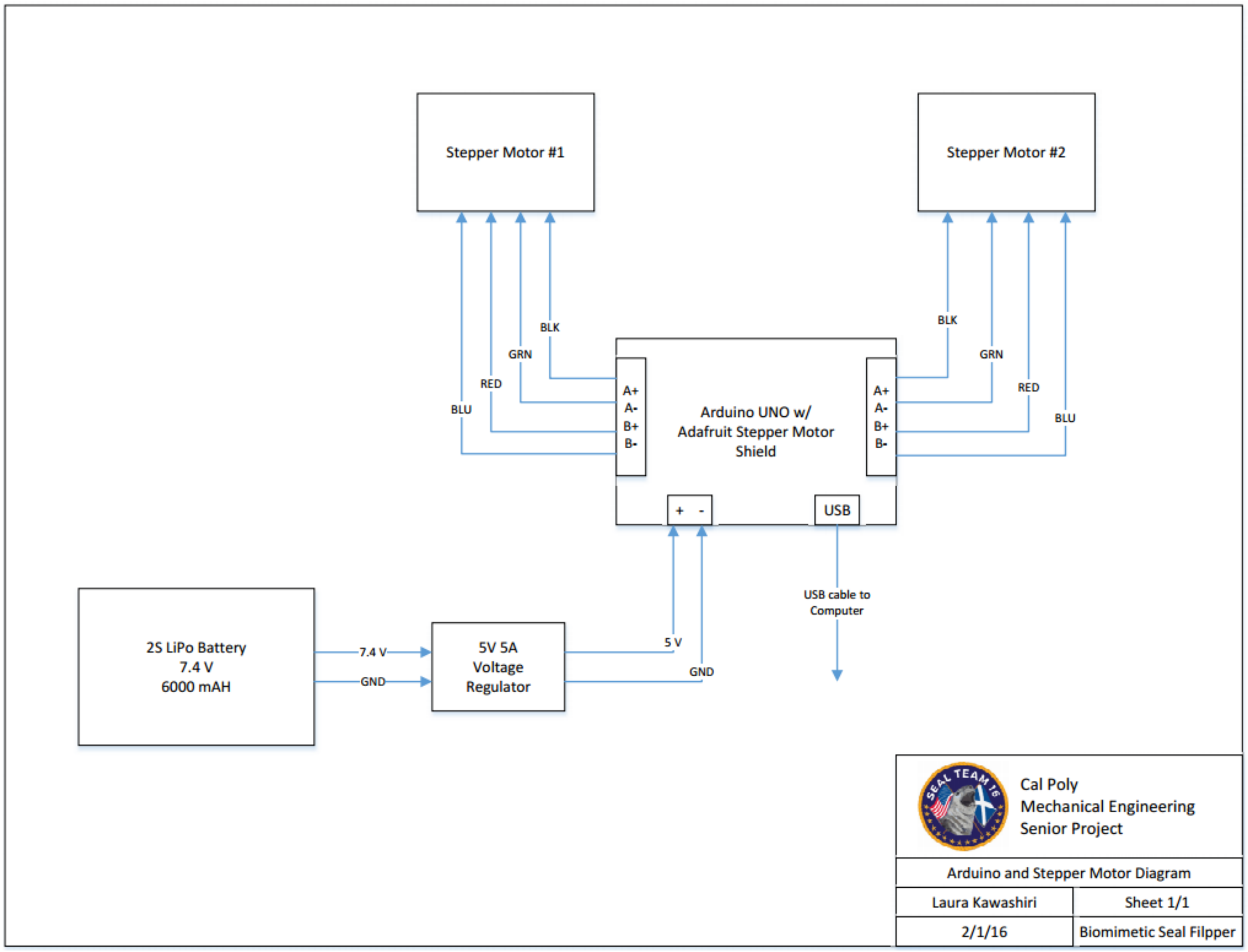


Figure 22. Wiring Diagram

Figure 23 shows a very general concept of how inputs into a GUI end up physically moving the flippers. The GUI does not affect the serial commands, but instead acts as a visually appealing interpretation of the serial window. As opposed to giving commands by typing out the string, the same commands would be sent by selecting buttons or moving sliders in an animated settings window. Because the creation of a GUI would require additional programming knowledge that stretches outside the scope of a Mechanical Engineering project, our prototype user interface consists of purely serial commands, for which the operation still maintains an intuitive feel. The creation of a GUI to accompany the current serial command processes, however, would provide an excellent project for someone with a stronger background in Computer Science to pursue, which will be discussed further in the future recommendations.

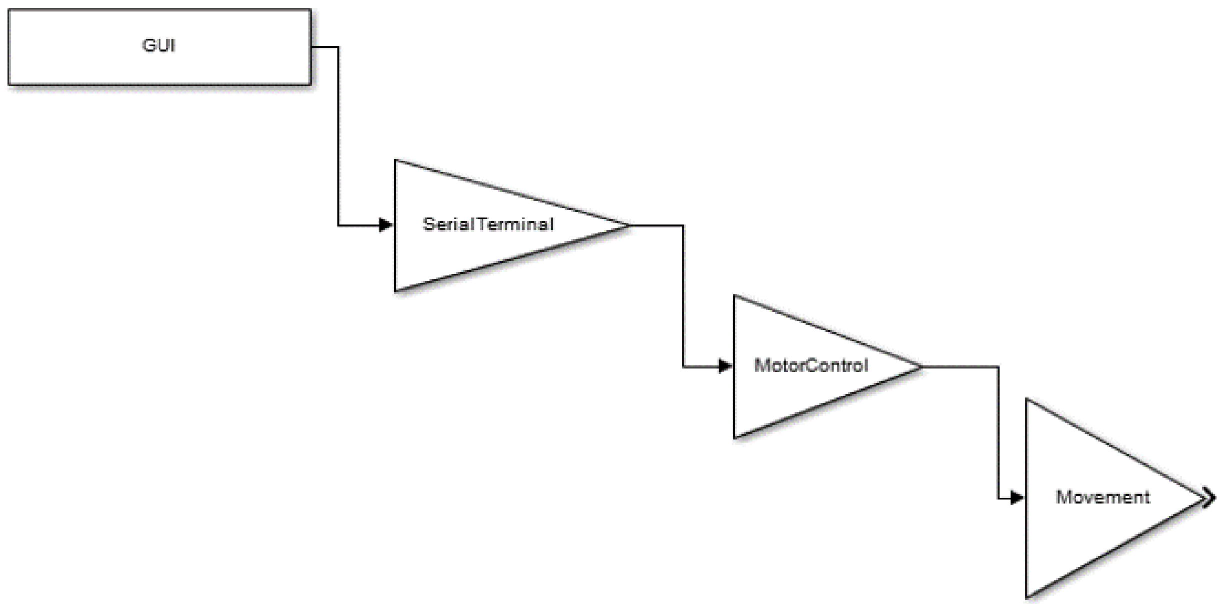


Figure 23. Basic coding flowchart from GUI inputs to movement

4.6 Safety, Maintenance, and Repair

Since this is a water-based project, water resistance is of the utmost importance when it comes to safety. The team has been careful to design for water-tight enclosures for all moving and electronic components.

When it comes to safety measures within the electronics and coding, the GUI provides a "maximum deflection" variable, which prevents the user from accidentally allowing the flipper to spin too far and collide with the water channel's wall or even the other flipper.

The team has put together a tool kit specifically designed for this rig for Dr. Doig. The tool kit hex wrenches, epoxy, Loctite, and other items necessary for maintenance of the rig. The idea is that the tool kit will allow Dr. Doig to fix any physical, mechanical problems he comes across as he continues to use the rig.

Besides the tool kit, we have purchased spares of each small part as well as a spare motor. The spare parts and spare motor should help extend the longevity of the rig, ideally lasting until Dr. Doig has concluded his research. Appendix J shows a user manual detailing the use and maintenance of the rig.

5 Product Realization

5.1 Manufacturing

The parts that required in-house manufacturing included the HDPE base plate, the motor planks, the bearing housings, and the drivetrain casings. The pieces for the base plate were cut from 0.5 inch and 0.25 inch thick HDPE sheet stock using the manual Bridgeport mills on campus. As opposed to the UHMW previously considered, the HDPE experienced minimal fraying at the edges, even for the shallow cuts of 0.1 inches, when cut at speeds greater than 1800 RPM and fed manually at a rapid rate. This method was used to effectively produce the positioning channels, the ruler slot, and the joints. The motor planks, however, proved to be the most difficult parts to manufacture, despite being made of the same material. The initial manufacturing process was to cut the planks from 1.5 inch wide strips of the 0.5 inch stock and mill away 0.25 inches of material from the bottom, leaving the positioning tabs corresponding to the channels. Unfortunately, thermal distortion due to the rapid removal of proportionally large amounts of material was not considered as a possible issue. This resulted in the planks curling inward due to the thermally induced shrinking of the milled side. In an attempt to correct this defect, the plank material underwent additional thermal molding, in which it was forced to warp in the opposite direction before being heated, as shown in Figure 24. This effort still proved unsuccessful, and new planks were constructed by cutting strips of the 0.25 inch material and attaching 0.25 inch thick tabs via epoxy and M2.5 screws that also secured the bearing housings. The bearing housings were created using a resin 3D printer, which worked well for this application. Lastly, the drivetrain casings were assembled by epoxying lexan sheets together at the seams into a box form. The RTV silicon adhesive seal was applied along the casing rim by temporarily attaching the casing to the motor plank and using the "cake icing" method to apply the silicon along the surface interface from the corner of a ziploc bag. Once cured, the casing was carefully peeled off the plank, leaving a water resistant silicon trim that sat flush with the plank surface.

Figure 24. Attempting to unwarp the planks by clamping them down and putting them in the oven.

5.2 Prototype and Planned Design Discrepancies

The basic structure of the design stayed consistent after the preliminary design phases. Originally, the motor planks were to be machined from ½ inch think HDPE, creating the protrusions which mate with the slots. However, difficulties performing so much machining on the plastic forced the team to start with ¼ inch HDPE and glue on additional ¼ inch pieces. This change required no rework of any other parts and does not alter the functionality of the plank in any way.

Due to a tolerance stack miscalculation, the bearing carriers supporting the horizontal shaft needed to be raised slightly to provide correct alignment of the motor and gears. This was done by simply changing the CAD model and performing another 3D printing operation with the cured resin system.

The team initially intended to employ the services of the Cal Poly Packaging Lab to create injection molded plastic cases for the electronics. Unfortunately, the professor who had the expertise to assist the team did not have time to help. Instead, the team created the cases out of professionally-cut acrylic.

Another late addition to the design was the rubber vibration isolators between the motor and its mount. These isolators dampen some of the chatter from the motors that occurs as it steps. These isolators also serve as spacers to take up some of the length of the screws as the 2.5 mm diameter chosen for the project are only created in 5 mm increments and the team did not want to perform additional machining on purchased items.

Aside from these modifications there are few discrepancies between our planned design and assembled prototype. However, the scope of the graphical user interface (GUI) changed as the project progressed so naturally the design did as well. The initial intent was to have a program window or similar with input boxes, buttons, selectors and drop-down menus. The team soon found that this type of interface is much more difficult to create when working with Arduino in the C language. For this reason, the more elementary, yet still functional and user-friendly serial input window was created. The code for testing is in place for a future group to easily create the GUI.

5.3 Future Manufacturing Recommendations

Future teams should note the issues presented with the stepper motor choice. A stepper motor is limited in that is no way for the motor to know its current positon. The precision can be accurate enough for the project's purposes, however, with no feedback loop to ensure position, a flipper could get knocked out of place with out the system accounting and adjusting for it. A simple DC servo motor may be a suitable option for future projects, especially since waterproof versions are readily available.

Additionally, the stainless steel shafts are not actually rust-proof. A future group may want to manufacture plastic shafts as the analysis in an earlier section show that the loading is quite negligible, and plastic is unlikely to incur corrosive damage in an aqueous environment.

Otherwise, the team believes their design to be quite sound and ready for years of testing.

6 Design Verification

Since the rig does not experience significant loading, impact or other stress, the functionality of our design was measured primarily on how accurately the flippers can be positioned. Therefore, the significant tests concentrated on the flipper motion. The other aspect that is crucial to the success of the rig is the flipper mounting method. This should be reliable, repeatable and convenient for the user. Several tests were dedicated to validating this component of our design. Other tests ensured that the rig will be compatible with the PVR system and prevent water from coming into contact with the electronics.

6.1 Test Descriptions

1. **Flipper Installation Test**: This is a test of the functionality of the flipper attachment method. The rig should be mounted on a stand such that the user has access to the drive shaft coupling. The test engineer will then install the flipper in using the shaft coupling. The flipper will then be located using the provided tool and secured with the set screw. The engineer should be able to

install the flipper without assistance in less than 30 seconds. This is a proof-of-concept exercise to understand the difficulties of working with such small components and delicate tolerances. The test must be repeated with the same flippers four times, once by each member of the team.

2. **Flipper Removal**: The rig will be mounted on the stand in the same way as in the previous test. The rig will be set up with the flipper already installed. The test engineer will then remove the flipper from the device and store all components. This task must also be performed in less than 30 seconds by each member of the team.
3. **Shaft Coupler Torque Test**: This test is to prove that the shaft couplings employed in our design will not slip during any experimentation. A slippage in the shaft coupler would negate any experimental data collected during a trial run as the displayed position would not reflect the actual flipper angle. For this test, a shaft will be mounted on a flipper and the other end of the shaft secured in the shaft coupling attached to another free shaft not connected to the rig at all. This free end will be secured in a vise. The end of the spring scale will be secured to a hole drilled in the flipper 1 inch from the shaft axis. The test engineer will then pull the spring scale to a force of 1 lbf perpendicular to the shaft axis. The flipper should not slip under this load for 5 of these complete cycles, starting with the shafts uncoupled.
4. **Horizontal Position Test**: This test is meant to validate the lateral positioning design of the rig. The rig will be set on the stand as in the first test with all components installed. The motor planks will then be moved from its initial position to a position 30 mm away and then back for a total of 3 cycles. The test engineer performing the exercise will comment on the difficulty of the exercise and the observations will be recorded. Next, the plans will be moved to a location 15 mm from the initial datum and back 3 times. Observations will be recorded for these trials. Finally, a step of less than 5 mm will be attempted 3 times. This test is intended to confirm that the user will be able to easily and accurately position the motor planks regardless of the distance of travel.
5. **Motor Step Response (dry)**: The rig will be set on the test stand with all components installed. The flipper will be mounted and correctly positioned using the positioning tool. The flipper angle indicator, pictured in Figure 25 will be installed in the shaft coupler. A protractor printed on paper will measure the angle of the indicator. The tests will be started at an angle of 0°. The operator will manually move the angle indicator back and forth to ensure that there is not significant friction applied on the motor from contact with the paper. As the indicator moves back and forth, it will leave a pencil mark across the angles of the protractor paper. This test will be performed for a total of 10 different step angles for each flipper. 3 steps must be less than 5° and 3 steps much be greater than 20°.
6. **Motor Frequency Response (dry)**: The rig will be set up as in test 5. During this test, the angle will be observed and test engineers will make note of angles that do not meet the 1° accuracy requirement. Another engineer will film the motion of the indicator with the slow-motion feature on the camera with a stopwatch also in the frame. This video will be used to time the travel of one period of indicator movement. This will be compared to the frequency commanded by the operator and discrepancies will be recorded.
7. **Repeatability Test**: This test is a combination of tests 1 and 5. The flipper rig shall be set on the test stand with the flippers left uninstalled. The test engineer must install and position the flipper at the correct starting angle. The flipper will be moved to a specified location and then commanded to return to the starting position. The engineer will then remove the flipper completely. The engineer will then repeat this test for a total of 10 runs, ensuring that the flipper moves to the same location every time and returns to the starting location when commanded. This will prove that experimental results will be consistent even when the flipper is removed and reinstalled at a later date.

8. **Dripproof Test**: This test will prove the waterproofing capabilities before the rig is exposed to any wet environments. No wiring will be connected during this test and no power should be introduced into the system. The engineer will place tissue paper and paper towels over the electrical components. Next, all components will be sealed in their respective waterproof housings as it would be in normal operation. The engineer will then perform the dripproof test procedure from Military Standard 108E section 4.3 found in Appendix I. However, the stipulated test duration of 60 minutes and the drip rate are excessive for the scope of this project so the engineer will perform the test for 3 minutes at half the drip rate.
9. **Static Motor Torque (wet)**: The rig will be placed in the water channel with the flow set to maximum. An angular potentiometer will be installed on the driven gear connected to the flipper shaft. The engineer will then input a large angle such at 60° into the script or GUI and command the flipper to move to this position. The flipper will remain at this position as the engineer will observe and record the effect the flow has on the flipper position. The engineer should not if the flipper vibrates, turns or slips on its shaft. The flipper shall remain in this position for a total of 1 minute.
10. **Motor Step response (wet)**: Test 5 will be repeated while the rig is on top of the water channel running at maximum flow. The potentiometer will be located on top of the gear attached to the flipper shaft. The results will again be recorded with the DAQ and compared to the flipper location output by our script/GUI. The engineer will observe the test and record observations for reporting.
11. **Motor Frequency Response (wet)**: Test 6 will be repeated while the rig is on top of the water channel running at maximum flow. The potentiometer will be located on top of the gear attached to the flipper shaft. The results will again be recorded with the DAQ and compared to the flipper location output by our script/GUI. The engineer will observe the test and record observations for reporting.
12. **Imaging**: This test will confirm that the rig is compatible with the PIV imaging system and produces useful images for data collection. This exercise will be performed with Dr. Doig so that he can confirm the results are satisfactory. This will serve as a commissioning process for the rig before we turn it over to him for lab use.
13. **Endurance Test:** This test will determine whether or not the rig can run extended tests without failure. A failure would be defined as needing a new battery, motors overheating, or a loss in positional accuracy.

6.2 Test Completion and Results

1. **Flipper Installation Test:** Each member of the team has installed flippers onto the rig multiple times. The rig was placed on the end of a table or flat surface, or the motor plank is simply taken off the base plate and set on its side, before the flipper shaft is inserted into the coupler. The set screw was then tightened with an Allen wrench when the flipper was positioned correctly. At first some members fumbled with the small set screw, but when they got the hang of it, each flipper installation took much less than 30 seconds, around 10 seconds each.
2. **Flipper Removal:** The test removal of the flippers went exactly as the installation. The team followed the exact same procedure as test 1, in reverse order. All members of the team were able to remove flippers in just about 7 seconds.
3. **Shaft Coupler Torque Test:** Torque was applied to each shaft while in the couplers secured with a set screw and no slippage was recorded, even when loaded far above the test load of 1 in-lb.

4. **Horizontal Position Test:** The user is easily able to adjust the horizontal position of the planks on the baseplate and slippage does not appear to be an issue. The user can use the sightline and the ruler to easily identify the exact distance (in mm) between flippers.
5. **Motor Step Response (dry):** For tests 5 through 7, the angle indicator tool and printed protractors were used to measure and record angle position and accuracy. The testing setup is shown in Figure 25. When inputting a degree step, the rig will move to that step within 1 degree accuracy for almost all angles. For unknown reasons to the team, steps of 20-25 degrees and steps of around 50 degrees will lose the 1 degree accuracy, but still be within 3-5 degrees.

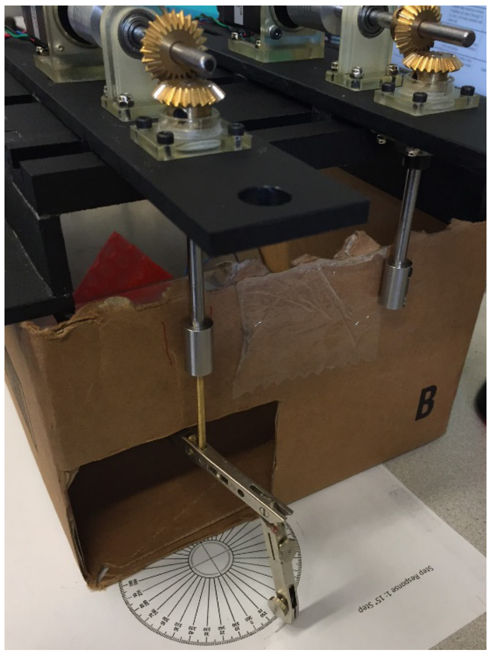


Figure 25. Dry step and frequency response test using angle indicator and printed protractors

6. **Motor Frequency Response (dry):** The frequency response test mimicked the inaccuracy in the 20-25 and 50 degree ranges, but for each sweep the angle indicator returned to the initial starting and ending positions. In other words, the motor swept to the same degree each time, but for the ranges stated above, the angle to which it swept was sometimes not within 1 degree of the stated angle.
7. **Repeatability Test:** Test 7 acted as a combination of tests 5 and 6. The number of cycles had no effect on the change in positional accuracy or step accuracy, leading to a very successful test.
8. **Dripproof Test:** The rig was handled with wet hands and also had water dripped on it before running. The acrylic housings and project box did an excellent job of preventing water from reaching electronic or moving parts.
9. **Static Motor Torque (wet):** Towards the end of spring quarter, Dr. Doig had many other students working on the water channel and there simply was not enough time to complete tests 9-11 because of it. Based on what the team knows of the rig, being in water compared to just in air should not change the step or frequency response of the motors at all. For continuation of this project, thorough wet testing should be performed to confirm optimum performance in a water channel.

10. **Motor Step Response (wet):** See test 9.
11. **Motor Frequency Response (wet):** See test 9.
12. **Imaging:** Dr. Doig moved the water channel into the wind tunnel room and away from the PIV system, so testing with that system was unable to be completed. The rig provides no obstructions to where the laser enters the channel, so the PIV system should theoretically work perfectly.
13. **Endurance Test:** The team decided to run probably its riskiest test in front of everyone at Senior Project Expo. They ran the flippers continuously while mounted on the channel for a total of 2:45. The rig was able to run the entire time on only one battery with charge still left for more testing. Additionally, the response of the motors was varied and changed by numerous people, indicating the code's robustness and ease of use. Final note is that the motors ran hotter than expected over the endurance test. This issue is discussed in greater depth in the next section.

6.3 DVP&R

The Design Validation Plan and Report matrix can be found in Appendix H. This matrix pairs the engineering specifications created for our project with the test that validates the design. The acceptance criteria for each test can also be found on this document. This document also shows abbreviated results of each test and additional notes.

7 Conclusions and Recommendations

Over the course of this project the most important lesson the team took home was the concept of a well designed project. The overall design was slightly refined from the preliminary design review to the critical design review, and remained virtually unchanged from the critical design review to the actual build and final report. The lack of necessary change to the design really helped the team put out a solid product, which looks exactly like the CAD model from the critical design review.

During Expo we got a chance to stress test the rig and run an extended test situation. The rig was able to easily perform a continuous 3 hour test cycle without overheating or needed to change the battery. The lack of airflow when the motors are incased in a the housing caused the motors to get hot, but a test of this duration is an unlikely scenario. It was observed that removing the water resistant housings caused the motors to stay at a safe operating range over the long test. Additionally Dr. Doig agreed that the chances of splashing are low so the motor covers are not required for all testing.The motor is able to handle a few drops on it from time to time, but it is not able to be submerged. Care should be taken to ensure that the motors do not overheat but are able to stay relatively dry.

Having a team member who had more expertise in computer science, mechatronics or programming would have been a valuable asset to this project. Since the mechanical components are not particularly complicated the success of the rig depends mostly on motor control and accuracy. A background in these areas may have resulted with the graphical user interface and control capabilities that Dr. Doig initially requested.

Overall, this project was a success as we met, or at least partially met, all of Dr. Doig's wants and constraints. The rig is functional and Dr. Doig is planning on using it starting the week of May 30th, 2016. For future use and expansion on this project, we recommend further refinement of the code and electronics of the rig, while maintaining the mechanical design.

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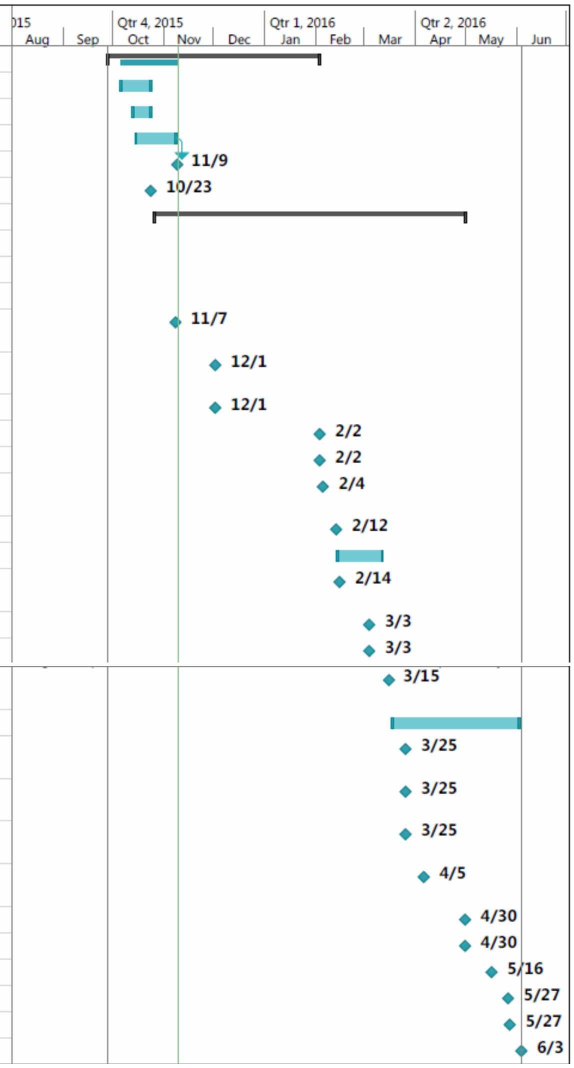
APPENDIX A: Quality Function Deployment

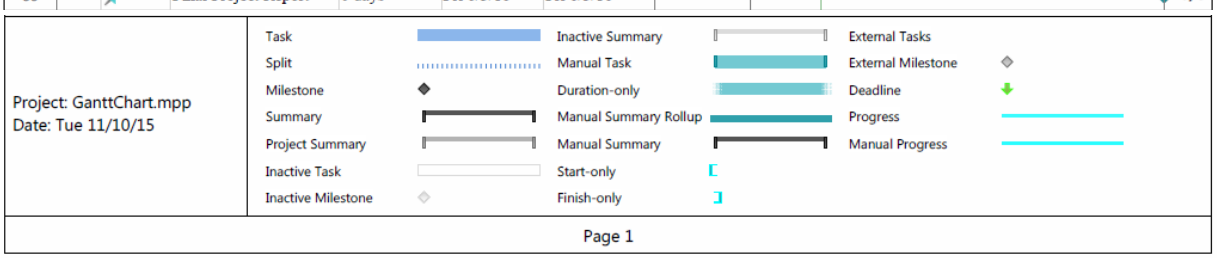
				Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
				Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	x	x	x	▲	x	▲	x	x	x	x	x	▼			
Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	Quality Characteristics (a.k.a. "Functional Requirements" or "Hows") / Demanded Quality (a.k.a. "Customer Requirements" or "Whats")	Width of Table	GUI	Standard Mount	Corrosion Resistant	Appropriate Motor	Design Factor	Electronic Casing	Test Section Width	Test Section Length	Test Section Height	Compatible with Facilities	Flipper Size			
1	9	14.5	8.0	Fits on Table	Θ				O	▲	▲	O	O	O	Θ				
2	9	7.3	4.0	Easy To use interface		Θ									O				
3	9	12.7	7.0	Easily Repeatable		O	Θ	O	O						▲	▲			
4	9	9.1	5.0	Modular/scalable			Θ	O	▲	O	▲				▲	O			
5	9	1.8	1.0	Long lifetime			O	Θ	O	O	O				▲				
6	9	16.4	9.0	Water Resistant				Θ			Θ								
7	9	18.2	10.0	Fits in test section	O							Θ	Θ	Θ		Θ			
8	3	3.6	2.0	Measurable through imaging			O								O	▲			
9	9	5.5	3.0	Easy setup		Θ	Θ	▲				O	▲	O	O	O			
10	9	10.9	6.0	minimal flow interference			Θ	O		▲		▲	▲	▲		Θ			
				Target or Limit Value	18.75"	yes	yes	yes	Brushless DC Motor	1.5	yes	7.25"	18"	9.5"	yes	Within Boundaries of Test Section			
				Difficulty (0-Easy to Accomplish, 10-Extremely Difficult)	0	9	5	6	2	7	3	2	2	2	3	4			
				Max Relationship Value in Column	9	9	9	9	3	3	9	9	9	9	9	9			
				Weight / Importance	185.5	152.7	360.0	267.3	96.4	58.2	176.4	234.5	223.6	234.5	203.6	321.8			
				Relative Weight	7.4	6.1	14.3	10.6	3.8	2.3	7.0	9.3	8.9	9.3	8.1	12.8			

Legend		
Θ	Strong Relationship	9
O	Moderate Relationship	3
▲	Weak Relationship	1
++	Strong Positive Correlation	
+	Positive Correlation	
−	Negative Correlation	
▼	Strong Negative Correlation	
▼	Objective Is To Minimize	
▲	Objective Is To Maximize	
x	Objective Is To Hit Target	

APPENDIX B: Gantt Chart

ID	Task Mode	Task Name	Duration	Start	Finish
1		**Design**	**77 days**	**Mon 9/28/15**	**Tue 2/2/16**
2		Spec	14 days	Tue 10/6/15	Fri 10/23/15
3		Research	9 days	Tue 10/13/15	Fri 10/23/15
4		Ideate	18 days	Thu 10/15/15	Sat 11/7/15
5		Pick Idea	0 days	Mon 11/9/15	Mon 11/9/15
13		Project Proposal	0 days	Fri 10/23/15	Fri 10/23/15
7		**Software**	**116 days**	**Mon 10/26/15**	**Sat 4/30/16**
8		Research			
9		Choose Software			
10		Code			
14		Prelim Design Review	0 days	Sat 11/7/15	Sat 11/7/15
15		Preliminary Design Report	0 days	Tue 12/1/15	Tue 12/1/15
16		Rough CAD model	0 days	Tue 12/1/15	Tue 12/1/15
17		Final Design Report	0 days	Tue 2/2/16	Tue 2/2/16
18		Final CAD	0 days	Tue 2/2/16	Tue 2/2/16
19		Critical Design Review	0 days	Thu 2/4/16	Thu 2/4/16
20		Redesign Due	0 days	Fri 2/12/16	Fri 2/12/16
6		Build	21 days	Sun 2/14/16	Fri 3/11/16
21		Order Parts for Prototype Build	0 days	Sun 2/14/16	Sun 2/14/16
22		PrototypeGUI/Coding	0 days	Thu 3/3/16	Thu 3/3/16
23		Prototype Build	0 days	Thu 3/3/16	Thu 3/3/16
24		Preliminary Test Report	0 days	Tue 3/15/16	Tue 3/15/16
11		Test	50 days	Fri 3/18/16	Thu 6/2/16
25		Final Update to Sponsor	0 days	Fri 3/25/16	Fri 3/25/16
26		Manufacturing and Test Review	0 days	Fri 3/25/16	Fri 3/25/16
27		Order Parts for Final Build	0 days	Fri 3/25/16	Fri 3/25/16
28		Order More Parts if Necessary	0 days	Tue 4/5/16	Tue 4/5/16
29		GUI/Coding Done	0 days	Sat 4/30/16	Sat 4/30/16
30		Build	0 days	Sat 4/30/16	Sat 4/30/16
31		Troubleshoot/Test	0 days	Mon 5/16/16	Mon 5/16/16
12		Expo	0 days	Fri 5/27/16	Fri 5/27/16
32		Senior Design Expo	0 days	Fri 5/27/16	Fri 5/27/16
33		Final Project Report	0 days	Fri 6/3/16	Fri 6/3/16



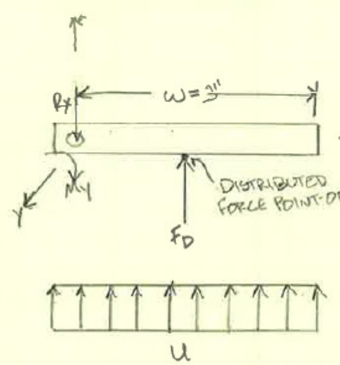


APPENDIX C: Preliminary Force Calculations

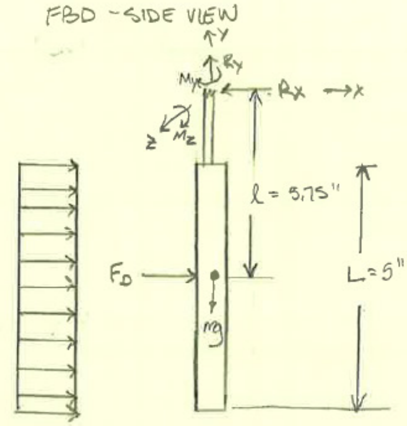
APPENDIX C — 11/09/15

CALCULATION OF FORCES CAUSED BY FLOW ON FLIPPER SHAFT

FBD TOP VIEW



FBD - SIDE VIEW



DRAG FORCE CALCULATION:

GOVERNING EQUATION: BERNOULLI'S

$$\left[P + \tfrac{1}{2}\rho U^2 + \rho g z\right]_{upstream} = \left[P_{stag} + \tfrac{1}{2}\rho U^2 + \rho g z\right]_{flipper}$$

(terms struck out: P and $\rho g z$ upstream = 0; $\tfrac{1}{2}\rho U^2$ and $\rho g z$ at flipper = 0)

$$P_{stag} = \tfrac{1}{2}\rho U^2$$

ASSUME
1) STEADY-STATE
2) INCOMPRESSIBLE
3) INVISCID
4) FULLY-DEVELOPED FLOW

MODIFY USING DRAG COEFFICIENT TO COMPUTE FORCE

$$F_D = \tfrac{1}{2}\rho u^2 A C_D$$

WHERE

$\rho = 1.94$ slugs/ft^3
$u = 5$ in/s $= .417$ ft/s
$A = \omega \times L = 15$ in^2 $= .104$ ft^2
$C_D = 1.9$

$$F_D = .033 \text{ lbf}$$

STATICS ANALYSIS:

$\sum F_x = 0$
$F_D - R_x = 0$
$F_D = R_x$
$R_x = .033$ lbf

$\sum F_y = 0$
$R_y - mg = 0$
$R_y = mg$

$\sum M_y = 0$
$F_D(\omega/2) - M_y = 0$
$M_y = F_D(\omega/2)$
$M_y = 0.004$ ft-lbf

$\Sigma M_z = 0$

$F_D(l) - M_z = 0$

$M_z = F_D(l)$

$M_z = .008$ ft-lbf

APPENDIX D: Design Hazard Identification Checklist

ME428/429/430 Senior Design Project 2015-2016

SENIOR PROJECT CRITICAL DESIGN HAZARD IDENTIFICATION CHECKLIST

Team: ______________________________ Advisor: ____________________

Y	N	
☐	✔	Do any parts of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points adequately guarded?
☐	✔	Does any part of the design undergo high accelerations/decelerations that are exposed to the user?
☐	✔	Does the system have any large moving masses or large forces that can contact the user?
☐	✔	Does the system produce a projectile?
☐	✔	Can the system to fall under gravity creating injury?
☐	✔	Is the user exposed to overhanging weights as part of the design?
☐	✔	Does the system have any sharp edges exposed?
☐	✔	Are there any ungrounded electrical systems in the design?
☐	✔	Are there any large capacity batteries or is there electrical voltage in the system above 40 V either AC or DC?
✔	☐	Is there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids when the system is either on or off?
☐	✔	Are there any explosive or flammable liquids, gases, dust, or fuel in the system?
☐	✔	Is the user of the design required to exert any abnormal effort and/or assume a an abnormal physical posture during the use of the design?
☐	✔	Are there any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
☐	✔	Will the system generate high levels of noise?
☐	✔	Will the product be subjected to extreme environmental conditions such as fog, humidity, cold, high temperatures ,etc. that could create an unsafe condition?
☐	✔	Is it easy to use the system unsafely?
✔	☐	Are there any other potential hazards not listed above? If yes, please explain on the back of this checklist.

For any "Y" responses, add a complete description on the reverse side. DO NOT fill in the corrective actions or dates until you meet with the mechanical and electrical technicians.

Description of Hazard	Corrective Actions to Be Taken	Planned Completion Date	Actual Completion Date
Battery in Use	Battery will be placed water proof project box away from the water channel, We are also using a 5 volt voltage regulator		
Electronics near water	All electronics will be placed in a waterproof project box away from the water channel		

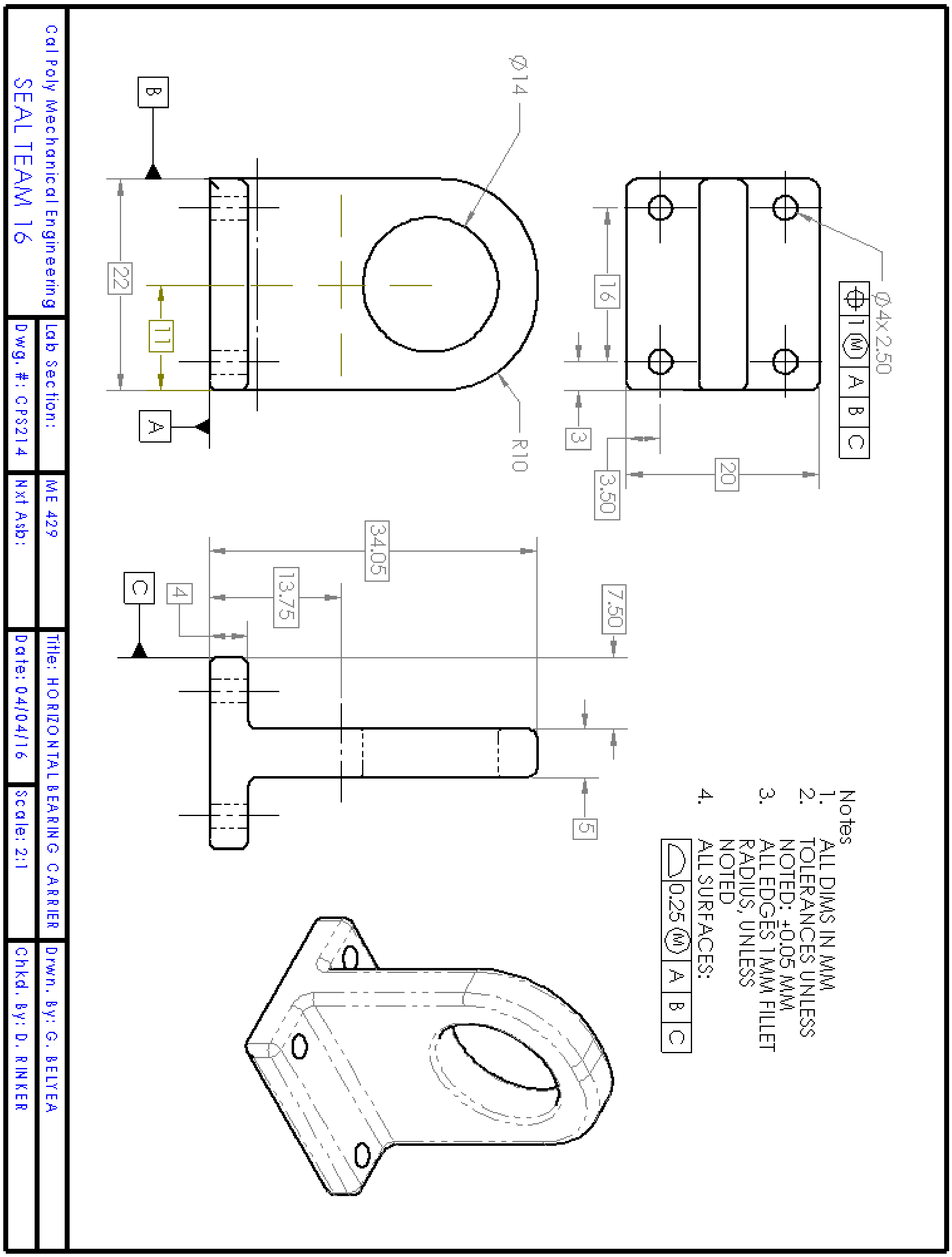
APPENDIX E: Bill of Materials

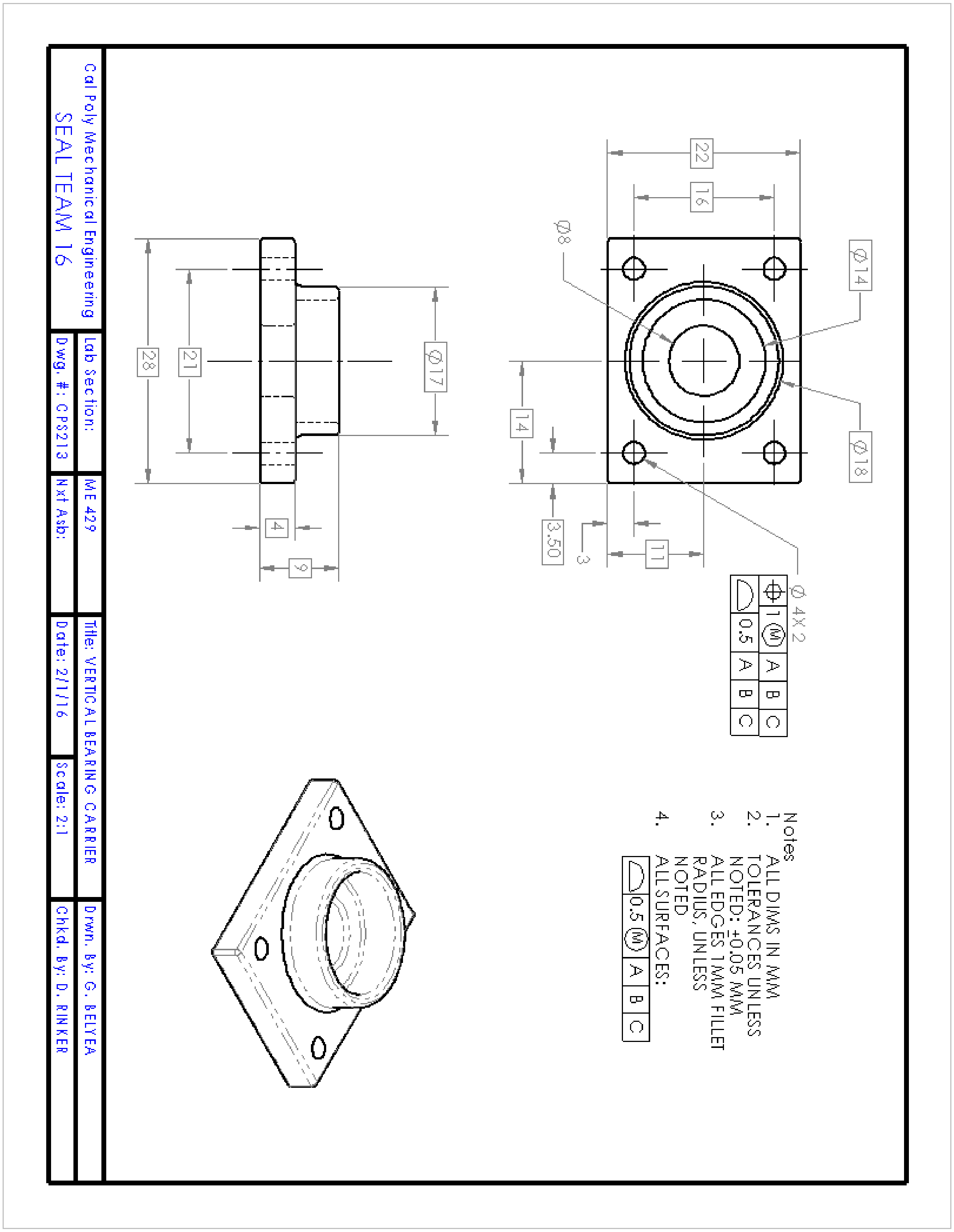
Bill of Materials						
CP Seals Test Rig				Total Project Cost:		$ 621.02
Subsystem	**Name**	**Part Number**	**Description**	**Qty. Needed**	**Unit Cost**	**Total Cost**
Plate	Base	CPS101	HDPE plate black thickness: 1/4" 12x12"	1	$9.14	$9.14
	Base	CPS102	HDPE plate black thickness: 1/2" 12x12"	1	$16.61	$16.61
	Channel Attachment	CPS103	3M 2228 Scotch Moisture Sealing Electrical Tape (10 ft roll)	1	$10.00	$10.00
	Ruler	CPS104	6" Stainless Steel Ruler (Standard + metric)	1	$5.65	$5.65
	Epoxy	CPS105	Marine-Grade Epoxy	2	$6.97	$13.94
Motor Mount	Motor Plank	CPS201	HDPE plastic sheet 1/4"	Part of CPS101	N/A	0
	NEMA 11 Bipolar Stepper Motor	CPS202	NEMA 11 (28.2 mm x 28.2 mm) mid holding torque 5mm shaft 0.67A 14oz.in/9.5Ncm 4 Leads	2 Plus spare	$18.50	$55.50
	12V Voltage Regulator	CPS203	3-30V to 12V regulator for motor	1	$15.00	$15.00
	Motor Mount Plate	CPS204	Stepper Motor Mount	2	N/A	0
	M2 Bearing Carrier Screw	CPS206	M2.5 x 15 mm	8 Bags	$2.05	$16.40
	M2 Bearing Carrier Nut	CPS207	M2.5 Nylock nut	4 Bags	$3.79	$15.16
	Motor Gear/ Flipper Gear	CPS208	5mm bore, 24t, 32P	2x + spares	$27.20	$27.20
	Flipper Gear	CPS209	5mm bore, 24t, 32P	2x	$5.99	$35.94
	Flipper Bearing	CPS210	5mm bore 10 qty.	1 pack of 10	$6.88	$6.88

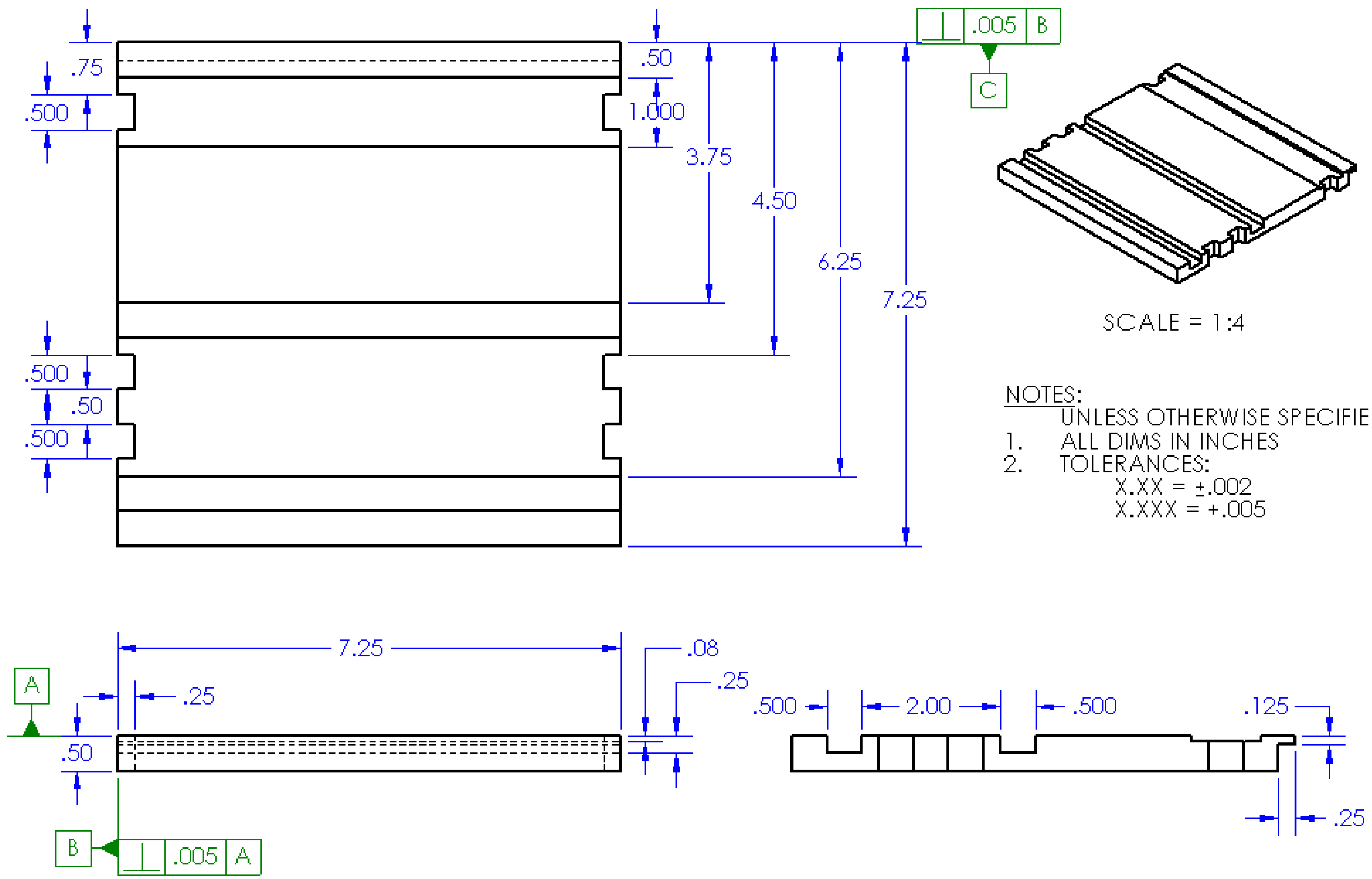
	Motor Bearing	CPS212	same as flipper bearing	account ed for		
	Motor Bearing Housing - Vertical	CPS213	CAD part	4	N/A	
	Motor Bearing Housing - Horizontal	CPS214	CAD part	2	N/A	
	Motor Shaft	CPS215	5 mm bar stock, 36" length	1	$4.74	$4.74
	Motor Shaft Coupler	CPS216	Aluminum Flex Shaft Coupler - 5mm to 5mm	2	$4.95	$24.75
	Motor Shaft Coupler	CPS217	1/8th in to 5mm	6	$4.99	$29.94
	5 mm Shaft Collar	CPS218	Ruland MSC-5-F Set Screw Shaft Collar, Black Oxide Steel, Metric, 5mm Bore, 10mm OD, 6mm Width (Pack of 4)	1	$9.98	$9.98
	1/8" Shaft	CPS301	Brass Round 1/8 inch Dia. 1 ft	2	$1.20	$2.40
	Stepper Shield	CPS401	Adafruit Motor/Stepper/Servo Shield for Arduino v2 Kit - v2.3 (drives 2 steppers)	1	$22.50	$22.50
Flipper Mount	Project box	CPS403	Enclosure for Arduino and battery (8x6x3")	1	$8.99	$8.99
Electronics	Arduino	CPS404	Arduino Uno R3	1	$24.95	$24.95
	5V Voltage Regulator	CPS405	5V 3A UBEC 2-5S Lipoly (7.2-21V)	1	$15	$15.00
	2s LiPo Battery	CPS406	DuraTrax 5000mah 2S2P 65~130C Hardcase Lipo Pack	2	$45	$90.00
	Battery Charger	CPS407	Duratrax 2-4s LiPo charger	1	$24.99	$24.99

	Plug Adaptor	CPS408	T Style Connector Male/Female with Insulating Caps (10 pairs)	1	$4.90	$4.90
	Fireproof LiPo Charge bag	CPS409	Lithium Polymer Charge Pack 25x33cm	1	$4.17	$4.17
	12 AWG Wire Black	CPS410	black wire 1 m	1	$2.20	$2.20
	12 AWG Wire Red	CPS411	red wire 1 m	1	$2.52	$2.52
Positioning Tool	Acrylic	CPS501	CAD Model	1	0	0
Tool Set	Display Tank`	Not used	6"x6"x12" Desktop Aquarium	1	$32.00	$32.00
	Loctite	CPS604	Blue Loctite - 6mL	1	$6.77	$6.77
	Grub Screw 2mm	CPS605	Ace Hardware	20	$0.15	$3.00
	Grub Screw 3/32"	CPS606	Ace Hardware	20	$0.15	$3.00
	Allen Wrench	CPS601	Husky Metric Allen Wrench Set	1	$7.99	$7.99
	Allen Wrench	CPS602	Husky Standard Measurement Allen Wrench Set	1	$7.99	$7.99

APPENDIX F: DRAWINGS

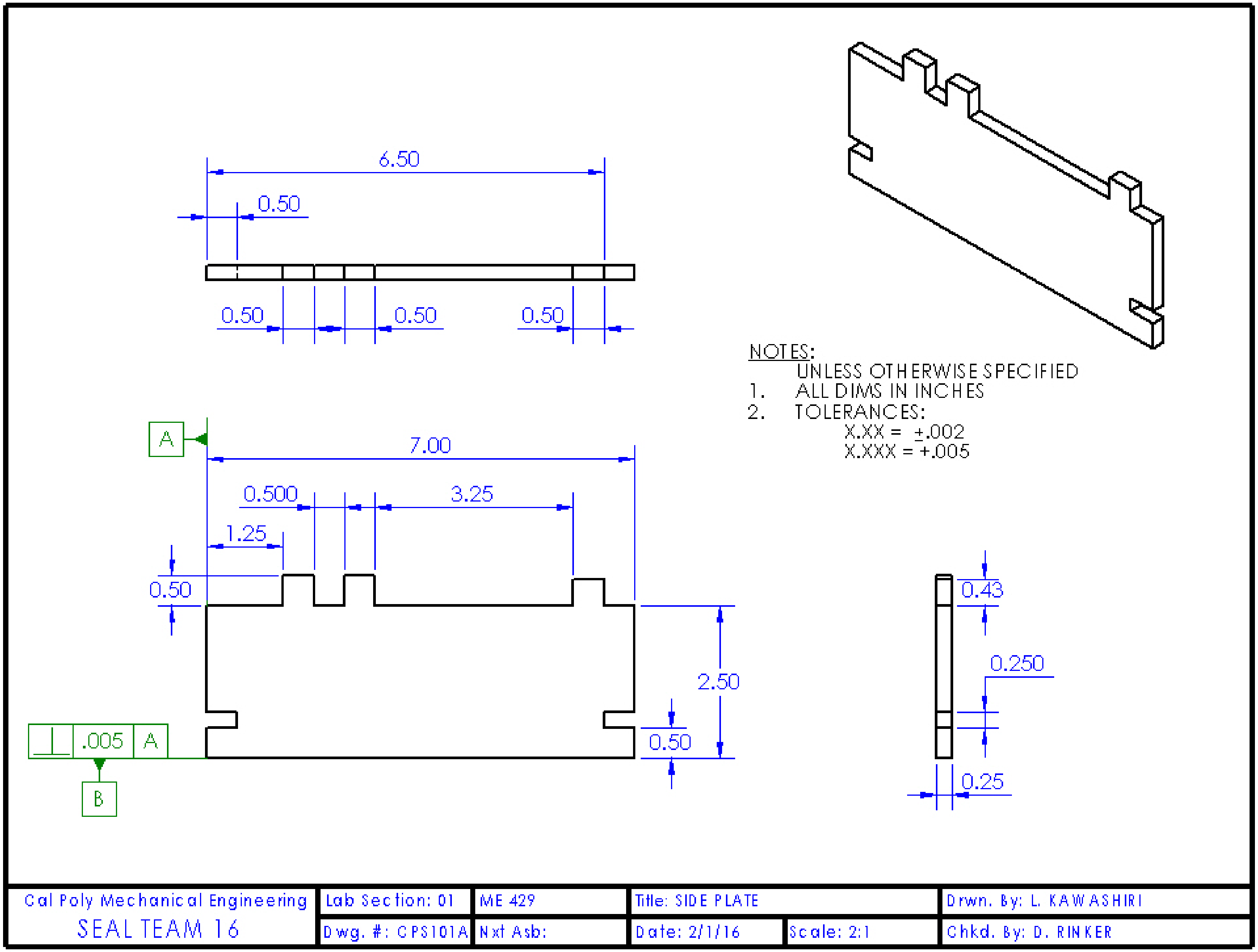


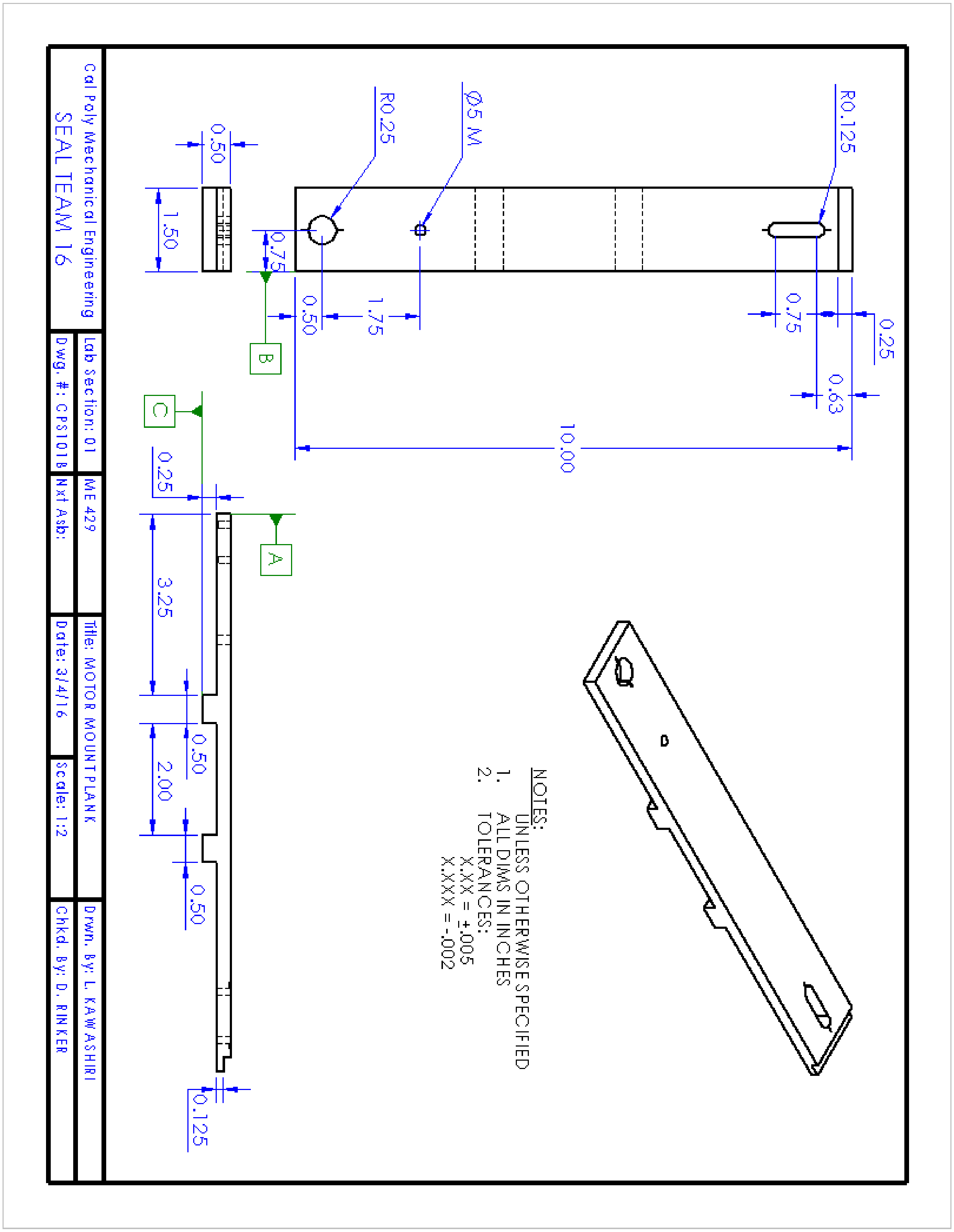

Cal Poly Mechanical Engineering
SEAL TEAM 16
Lab Section:
Dwg. #: CPS213
ME 429
Nxt Asb:
Title: VERTICAL BEARING CARRIER
Date: 2/1/16
Scale: 2:1
Drwn. By: G. BELYEA
Chkd. By: D. RINKER
Notes
1. ALL DIMS IN MM
2. TOLERANCES UNLESS NOTED: ±0.05 MM
3. ALL EDGES 1MM FILLET RADIUS, UNLESS NOTED
4. ALL SURFACES:
0.5 Ⓜ A B C
22
16
Ø8
Ø14
Ø18
14
3.50
3
11
Ø 4X 2
1 Ⓜ A B C
0.5 A B C
28
21
Ø17
4
9

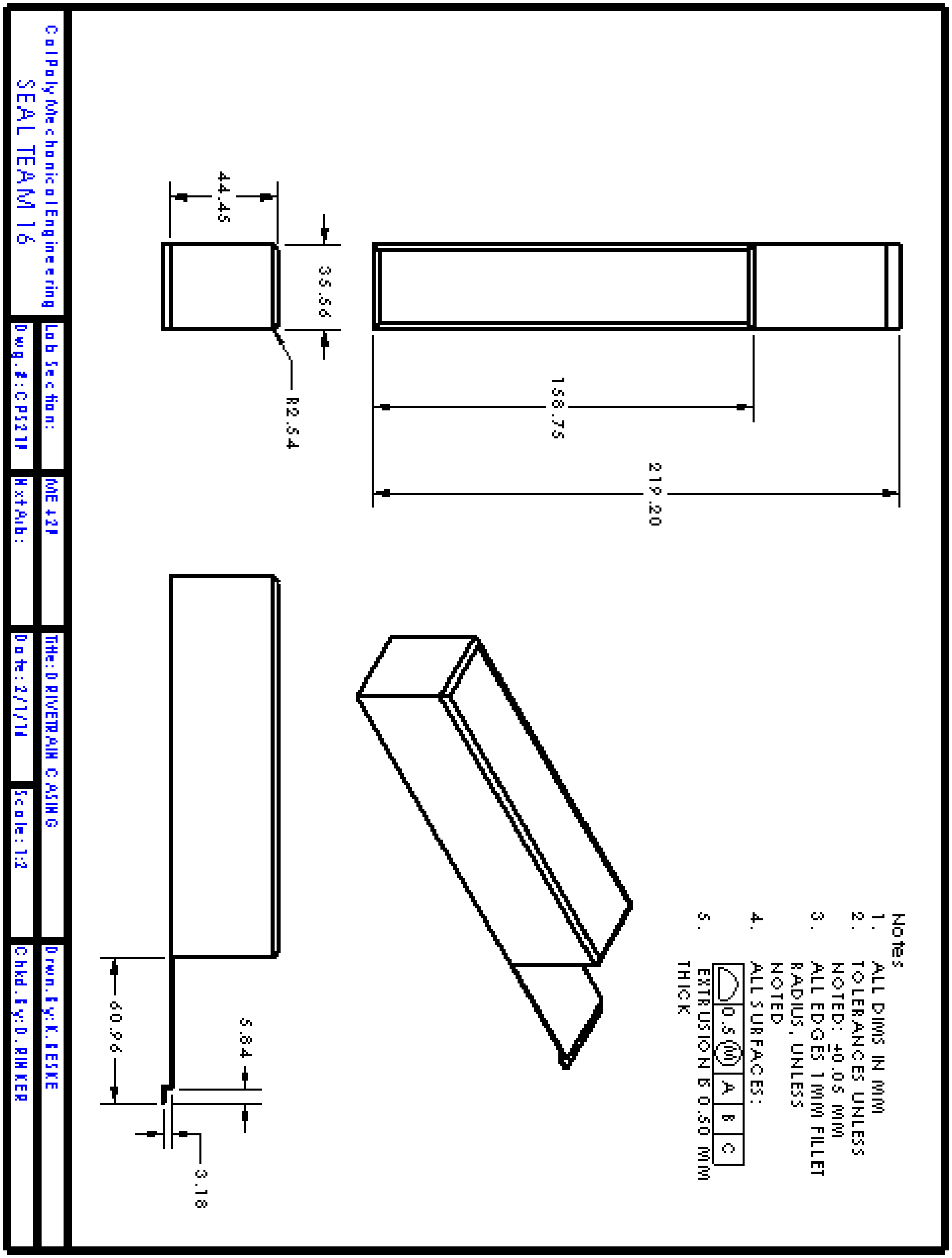


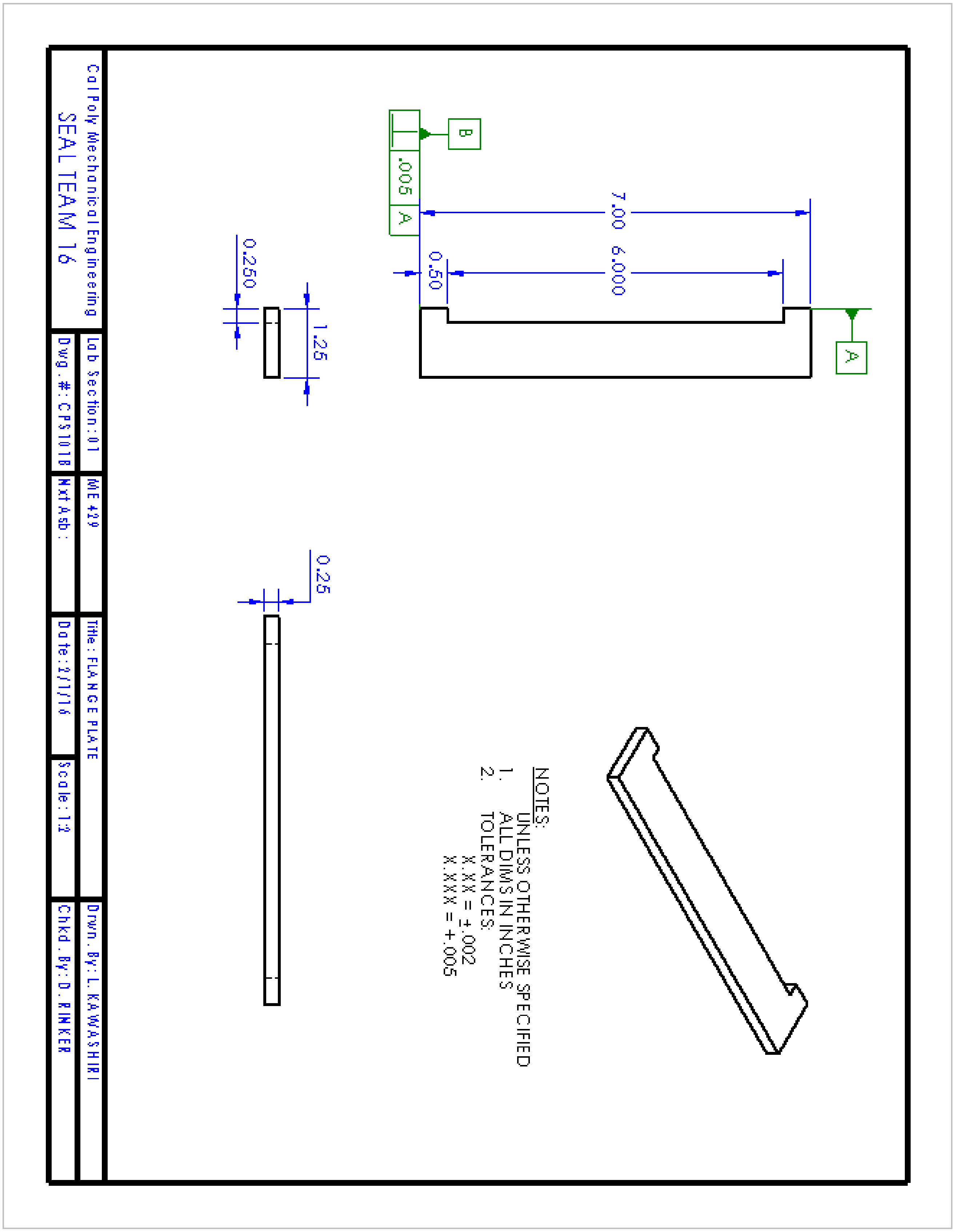
NOTES:
UNLESS OTHERWISE SPECIFIED
1. ALL DIMS IN INCHES
2. TOLERANCES:
X.XX = ±.002
X.XXX = +.005

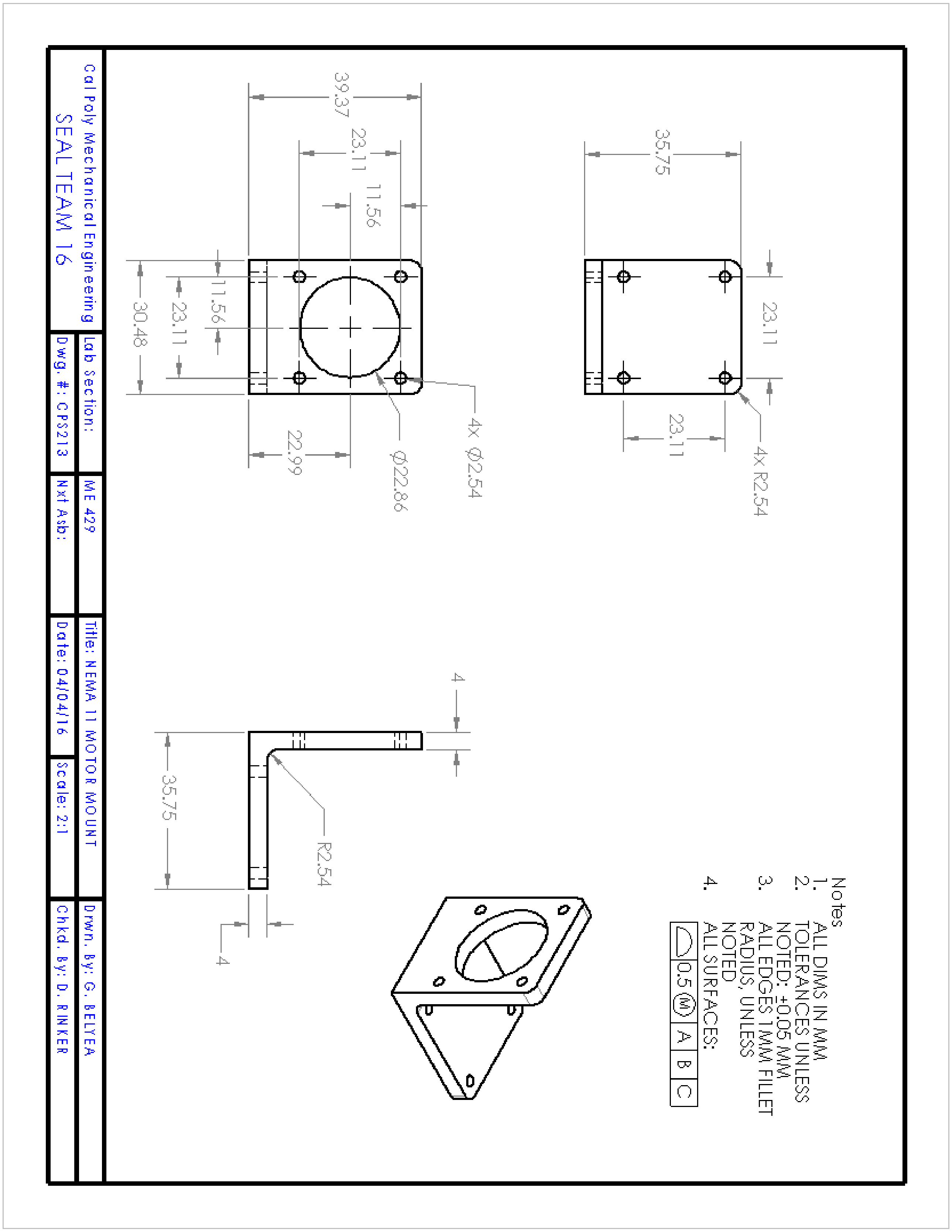
Cal Poly Mechanical Engineering SEAL TEAM 16	Lab Section: 01	ME 429	Title: BASE PLATE		Drwn. By: L. KAWASHIRI
	Dwg. #: CPS102	Nxt Asb:	Date: 2/1/16	Scale: 1:2	Chkd. By: D. RINKER


6.50
0.50
0.50
0.50
0.50
A
7.00
0.500
3.25
1.25
0.50
2.50
0.50
.005
A
B
0.43
0.250
0.25
NOTES:
UNLESS OTHERWISE SPECIFIED
1. ALL DIMS IN INCHES
2. TOLERANCES:
X.XX = ±.002
X.XXX = +.005
Cal Poly Mechanical Engineering
SEAL TEAM 16
Lab Section: 01
ME 429
Title: SIDE PLATE
Drwn. By: L. KAWASHIRI
Dwg. #: CPS101A
Nxt Asb:
Date: 2/1/16
Scale: 2:1
Chkd. By: D. RINKER

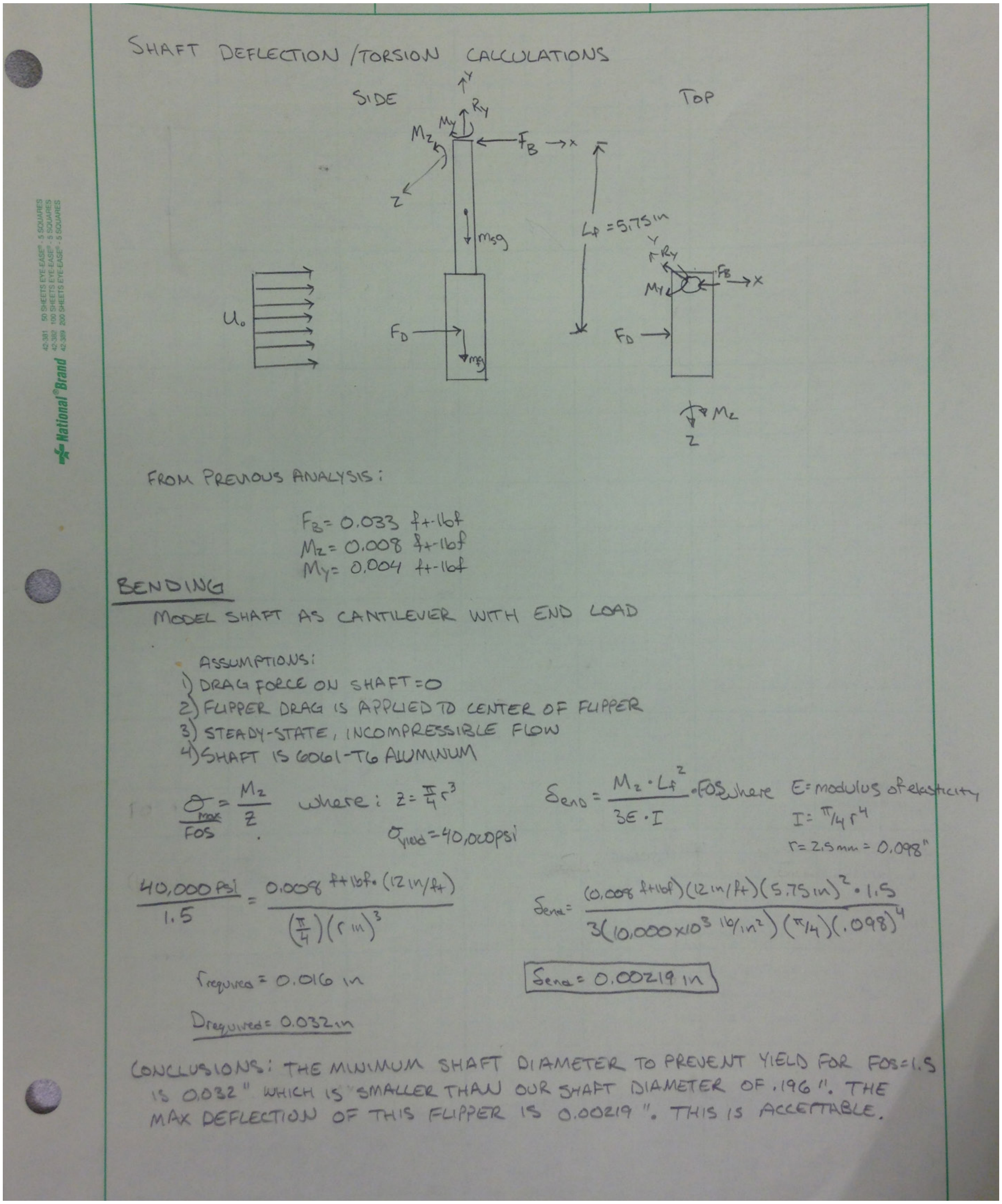

Cal Poly Mechanical Engineering
SEAL TEAM 16
Lab section: 01
ME 429
Title: MOTOR MOUNT PLANK
Drwn. By: L. KAWASHIRI
Dwg. #: CPS1018
Nxt Asb:
Date: 3/4/16
Scale: 1:2
Chkd. By: D. RINKER
NOTES:
1. UNLESS OTHERWISE SPECIFIED ALL DIMS IN INCHES
2. TOLERANCES:
X.XX = ±.005
X.XXX = ±.002
R0.25
Ø5 M
R0.125
0.50
1.50
0.75
0.50
1.75
0.75
0.25
0.63
10.00
A
B
C
0.25
3.25
0.50
2.00
0.50
0.125


Notes
1. ALL DIMS IN MM
2. TOLERANCES UNLESS NOTED: ±0.05 MM
3. ALL EDGES 1MM FILLET RADIUS, UNLESS NOTED
4. ALL SURFACES:
0.5 Ⓜ A B C
5. EXTRUSION 6 0.50 MM THICK
44.45
35.56
R2.54
158.75
219.20
60.96
5.84
3.18
Cal Poly Mechanical Engineering
SEAL TEAM 16
Lab Section:
ME 429
Title: DRIVETRAIN CASING
Drwn. By: K. FESKE
Dwg. #: CP5210
Nxt Asb:
Date: 2/1/11
Scale: 1:2
Chkd. By: D. RINKER


B
.005
A
7.00
6.000
0.50
A
0.250
1.25
0.25
NOTES:
1. UNLESS OTHERWISE SPECIFIED ALL DIMS IN INCHES
2. TOLERANCES:
X.XX = ±.002
X.XXX = +.005
Cal Poly Mechanical Engineering
SEAL TEAM 16
Lab Section:01
Dwg.#:CPS101B
ME 429
Nxt Asb:
Title: FLANGE PLATE
Date:2/1/16
Scale:1:2
Drwn. By: L. KAWASHIRI
Chkd. By: D. RINKER


Cal Poly Mechanical Engineering
SEAL TEAM 16
Lab Section:
ME 429
Title: NEMA 11 MOTOR MOUNT
Drwn. By: G. BELYEA
Dwg. #: CPS213
Nxt Asb:
Date: 04/04/16
Scale: 2:1
Chkd. By: D. RINKER
Notes
1. ALL DIMS IN MM
2. TOLERANCES UNLESS NOTED: ±0.05 MM
3. ALL EDGES 1MM FILLET RADIUS, UNLESS NOTED
4. ALL SURFACES:
0.5 Ⓜ A B C
39.37
23.11
11.56
30.48
22.99
Ø22.86
4x Ø2.54
35.75
4x R2.54
4
R2.54

APPENDIX G: Shaft Stress Calculations



SHAFT DEFLECTION / TORSION CALCULATIONS

SIDE — TOP

FROM PREVIOUS ANALYSIS:

$F_B = 0.033$ ft-lbf
$M_z = 0.008$ ft-lbf
$M_y = 0.004$ ft-lbf

BENDING

MODEL SHAFT AS CANTILEVER WITH END LOAD

ASSUMPTIONS:
1) DRAG FORCE ON SHAFT = 0
2) FLIPPER DRAG IS APPLIED TO CENTER OF FLIPPER
3) STEADY-STATE, INCOMPRESSIBLE FLOW
4) SHAFT IS 6061-T6 ALUMINUM

$\frac{\sigma_{max}}{FOS} = \frac{M_z}{Z}$ where: $Z = \frac{\pi}{4} r^3$

$\sigma_{yield} = 40{,}000$ psi

$\delta_{end} = \frac{M_z \cdot L_f^2}{3E \cdot I} \cdot FOS$ where E = modulus of elasticity, $I = \frac{\pi}{4} r^4$

$r = 2.5$ mm $= 0.098''$

$$\frac{40{,}000 \text{ psi}}{1.5} = \frac{0.008 \text{ ft-lbf} \cdot (12 \text{ in/ft})}{\left(\frac{\pi}{4}\right)(r \text{ in})^3}$$

$$\delta_{end} = \frac{(0.008 \text{ ft-lbf})(12 \text{ in/ft})(5.75 \text{ in})^2 \cdot 1.5}{3(10{,}000 \times 10^3 \text{ lb/in}^2)(\pi/4)(.098)^4}$$

$r_{required} = 0.016$ in

$\delta_{end} = 0.00219$ in

$D_{required} = 0.032$ in

CONCLUSIONS: THE MINIMUM SHAFT DIAMETER TO PREVENT YIELD FOR FOS = 1.5 IS 0.032" WHICH IS SMALLER THAN OUR SHAFT DIAMETER OF .196". THE MAX DEFLECTION OF THIS FLIPPER IS 0.00219". THIS IS ACCEPTABLE.

TORSIONAL DEFLECTION

$$\theta = \frac{M_y \cdot L_F}{J \cdot G} \cdot FOS$$ where: J = Polar moment of inertia $= \frac{\pi r^4}{2}$

G = modulus of rigidity = 3.8×10^6 psi

$$\theta = \frac{(0.004\ ft{\cdot}lbf)(12\ in/ft)(5.75\ in)(1.5)}{\frac{\pi (.098\ in)^4}{2} \cdot 3.8 \times 10^6\ psi}$$

$\theta = 0.000752$ radians

$= 0.043°$

CONCLUSIONS: THE TORSIONAL DEFLECTION OF OUR 5 mm SHAFT OF 0.043° IS INSIGNIFICANT.

APPENDIX H: Design Validation Procedure and Report

	TEST PLAN									TEST REPORT			
Item No	Specification or Clause Reference	Test Description	Acceptance Criteria	Test Responsibili	Test Stage	SAMPLES TESTED Quantity	SAMPLES TESTED Type	TIMING Start date	TIMING Finish date	TEST RESULTS Test Result	TEST RESULTS Quantity Pass	TEST RESULTS Quantity Fail	NOTES
1	Spec. #8D from Table 1. Engineering Specifications	Shaft Installation (dry)	The test engineer should be able to install the flipper and adjust it to the correct angular position in less than 30 seconds	Team	CV	2	Flipper shaft, coupler, driving shaft	4/5/2016	4/5/2016	Installation took no longer than 10 seconds for any team member	2	0	
2	Spec. #8D from Table 1. Engineering Specifications	Shaft Removal (dry)	Should not take excessive force to remove and should be accomplished in less than 30 seconds	Team	CV	2	Flipper shaft, coupler, driving shaft	4/5/2016	4/5/2016	Removal took no longer than 7 seconds for any team member	2	0	
3	Spec. #8C from Table 1. Engineering Specifications	Shaft Coupler Torque Test (dry)	The shaft couplers should keep shafts stationary under a torque of 1 in-lb	Kurt	CV	2	Flipper shaft, coupler, driving shaft	4/5/2016	4/5/2016	Test was successful and slippage was not recorded even when loaded far above test	2	0	
4	Spec. #9 from Table 1. Engineering Specifications	Horizontal Position Test (dry)	Motor plank should be able to be positioned in 1mm increments on base plate	Kurt	CV	2	Motor planks and base plate	5/20/2016	5/20/2016	The user is easily able to adjust the motor planks 1 mm at a time and can confirm the change with the ruler	2	0	
5	Spec. #7D from Table 1. Engineering Specifications	Motor Step (dry)	Motor should be able to move flipper from any position to a desired position within 1°	Team	DV	2	Whole fixture	5/20/2016	5/20/2016	Maintains 1 degree accuracy most of the time, occasionally varies to 3-5 degree accuracy	7	5	
6	Spec. #7C and #7D from Table 1. Engineering Specifications	Motor Frequency Response (dry)	Motor should be able to maintain flipper location accuracy within 1° during frequency input test	Team	DV	2	Whole fixture	5/20/2016	5/20/2016	Rig consistently returns to exact starting and ending degree positions for each sweep	12	0	
7	Spec. #8D from Table 1. Engineering Specifications	Repeatability Test (dry)	Flipper step response should maintain accuracy through 10 cycles of mount, position and removal	Team	DV	2	Whole fixture	5/20/2016	5/20/2016	Positional accuracy is unaffected by number of cycles	12	0	
8	Spec. #4 from Table 1. Engineering Specifications	Dripproof Test: ML-STD 103E	Water should not come in contact with motor, arduino, battery or exposed wiring when system is splashed or handled with	Kurt	DV	2	Whole fixture, water channel	5/21/2016	5/21/2016	The project box and acrylic housings both do a good job of stopping water from dripping onto electronics	2	0	
9	Spec. #5A from Table 1. Engineering Specifications	Holding/Static Motor Torque (wet)	Flipper should not rotate when positioned at an extreme angle in water flow	Team	DV	2	Whole fixture, water channel	-	-	Channel was either in use or drained late spring quarter, wet testing was unable to be completed			
10	Spec. #5B from Table 1. Engineering Specifications	Motor Step (wet)	Motor should be able to move flipper from any position to a desired position within 1°	Team	DV	2	Whole fixture, water channel	-	-	Channel was either in use or drained late spring quarter, wet testing was unable to be completed			
11	Spec. #5B and #7D from Table 1. Engineering Specifications	Motor Frequency Response (wet)	Motor should be able to maintain flipper location accuracy within 1° during frequency input test	Team	DV	2	Whole fixture, water channel	-	-	Channel was either in use or drained late spring quarter, wet testing was unable to be completed			
12	Spec. #11 from Table 1. Engineering Specifications	Imaging	Clear/accurate imaging should be achieveable with system	Team + Dr. Doig	DV	1	Whole fixture, water channel, PIV	-	-	Channel was moved from the room with the PIV system, so testing will have to be delayed for Dr. Doig			

APPENDIX I: MIL-STD-108E: Drip-proof Test Procedure

3.3 Design requirements for hazardous atmospheres.

3.3.1 *Dust-ignition proof.* The purchaser shall indicate the type of hazardous dust involved. Applicability of the National Electric Code, if required, shall also be specified by purchaser.

3.3.2 *Explosionproof.* The purchaser shall indicate the specific hazardous gas or vapor involved. In addition, the purchaser shall designate which of the following requirements apply.

(a) National Electric Code.

(b) MIL-STD-810.

(c) Special Naval shipboard requirements (See MIL-E-2036).

3.4 Protection against contact with external fans. Fans which are external to the basic equipment enclosure (example: totally enclosed, fan-colled motor) shall have protective covers, grills or screens to prevent accidental contact with the moving parts. Openings in the covers, grills or screens shall be of such size that a 0.50 inch diameter rod will not pass through. On spraytight, fan-cooled and watertight fan-cooled machines drain holes shall be provided to prevent accumulation of water in the fan housing.

3.5 Construction. Enclosures, including protective covers, grills and screens shall be of rigid construction, inflexible to the firm touch.

4. TESTS AND DEFINITIONS

4.1 Procedures. The following test procedures are applicable to specific degrees of enclosure for environmental protection. Tests shall be conducted to the extent specified by the equipment specification or as otherwise required by the contract or order, and when so specified shall form a part of the inspection procedure for the equipment. Tests apply to the enclosed equipment (enclosure with contents) except that dust-tight and watertight enclosures for portable equipment may be tested without the contents, provided that the contents are not to be attached to the enclosure. Failure to meet the specified requirements, including the di-electric and insulation resistance requirements of the equipment specification following enclosure tests described herein shall be cause for rejection.

4.2 Airtight. Tests for airtightness shall be conducted with both of the following initial conditions.

(a) Internal air pressure 10 p.s.i. above external air pressure.

(b) Internal air pressure 10 p.s.i. below external air pressure.

Total time of each test shall be 24 hours minimum. The equipment operating sequence shall be as follows: ON—8 hours, OFF—4 hours minimum, ON—8 hours; OFF—4 hours minimum. A change in pressure difference (internal minus external or external minus internal pressure) of more than 0.6 p.s.i.g. during either test, after corrections for changes in barometric pressure and temperature, shall be cause for rejection

4.3 Dripproof (15 degrees) and dripproof (45 degrees). Visual examination or actual drip test may be used to determine the ability of the enclosed equipment to operate satisfactorily under the defined conditions. If neither method is specified in the equipment specification or by the contract or order, either may be used. Visual examination is intended to determine the ability of the enclosure to exclude falling drops of liquid or solid particles. Such exclusion is not necessarily required of the enclosure (see Table I). If the enclosed is of such design that falling drops of liquid or solid particles appear to be able to enter, the ability of the enclosed equipment to operate satisfactorily under the defined conditions can be determined only by further examination of equipment within the enclosure or by actual drip test.

(a) *Visual examination.* Enclosed equipment shall be visually examined for the presence of the following features and characteristics when in its normal position or inclined in any direction at angles not exceeding the specified 15° or 45°.

(1) There are no openings directly exposed to falling drops of water or solid particles. Openings where provided on exposed surfaces shall be protected by louvers or suitably covered.

(2) All removable access plates or covers on enclosure surfaces exposed to falling drops of water shall have gaskets. Doors and door openings on exposed enclosure surfaces shall be of such design as to prevent the entry of falling drops of water.

(3) There shall be no paths on the surface of the enclosure which drops of liquid or solid particles will follow and run into the enclosure.

(b) *Drip test.* The enclosed equipment shall be placed below a device that drips or sprinkles water over the entire enclosed equipment. (Examples of suitable test devices are the test equipment described in International Electrotechnical Commission Publication 144 and the rain chamber used for MIL-STD-810, Method 506 tests.) The minimum amount of water shall be 1000 cubic inches per square foot of area covered by the drip or sprinkle in 60 minutes. The dripping or sprinkle rate and distribution shall be approximately uniform. The enclosed equipment shall be oriented in 5 different positions during the test; normal position and inclined at the maximum angle (15° or 45°) forward, backward and to each side. The minimum time in each position shall be 12 minutes; 8 minutes operating and 4 minutes OFF. Failure of the equipment to operate satisfactorily or accumulation of water within the enclosure shall be cause for rejection.

4.4 Dust-ignition proof. Tests shall be as specified by the equipment specification or purchasing activity.

4.5 Dustproof. Tests shall be in accordance with Method 510, Dust test of MIL-STD-810, except that the test at an ambient temperature of 145°F should be omitted for equipment not designed to operate at that temperature. The equipment shall be operated during the test. Failure of the equipment to operate satisfactorily or accumulation of dust within the enclosure that would lead to eventual unsatisfacory operation shall be cause for rejection.

4.6 Dust-tight. Testing shall be in accordance with MIL-STD-810, except that the test at an ambient temperature of 145°F should be omitted on equipment not designed to operate at that temperature. Entry of any dust, revealed by subsequent disassembly and examination, shall be cause for rejection.

4.7 Explosionproof. Testing shall be in accordance with the applicable enclosure or environmental testing specification (see

APPENDIX J: Operator's Manual

Rev. A // May-2016 // G. Belyea

Operator's Manual:

Seal Team 16 Flipper Rig

1. Introduction/Safety
   We hope you have get meaningful results using the Seal Team 16 Flipper Rig. This rig was designed and build by Cal Poly Mechanical Engineering students for their senior project in 2016. This is meant to be a brief introduction to the use and maintenance of the device. For a full part description and design specifications, please refer to the report in Cal Poly's digital commons available through lib.calpoly.edu and searching for "Biomimetic Seal Flipper Rig"

   Disclaimer: the model you are about to use is a prototype and may not be perfect! Additionally you will be dealing with electricity and water! Please exercise caution when using or modifying the rig.

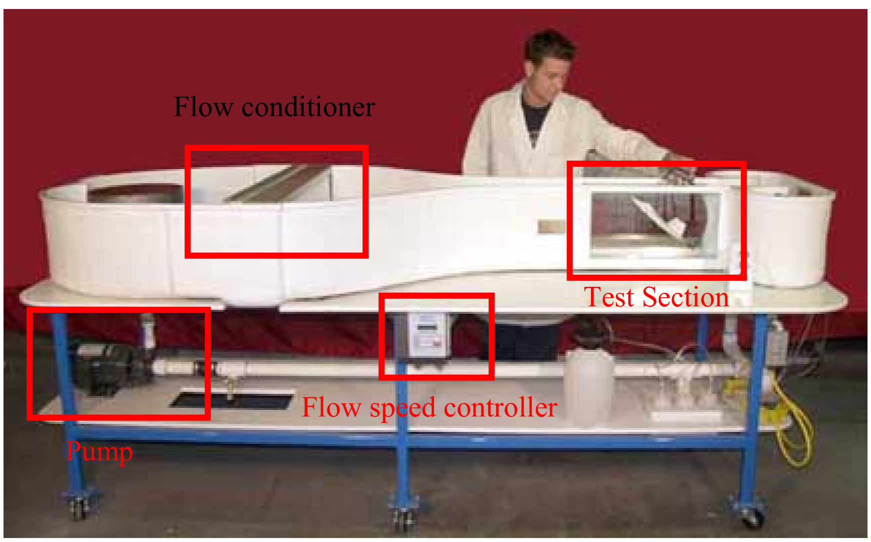


Figure 14. Rolling Hills Research Corporation Model 0710 University Desktop Water Channel.

For water channel operation refer to the user guide online:

"University Desktop Water Tunnel Model 0710." *Rolling Hills Research Corporation*. N.p., n.d. Web. 4 Nov. 2015.

http://www.rollinghillsresearch.com/Water_Tunnels/Brochures/Model_0710_&_Experiment_Overview.pdf

2. Description of Parts

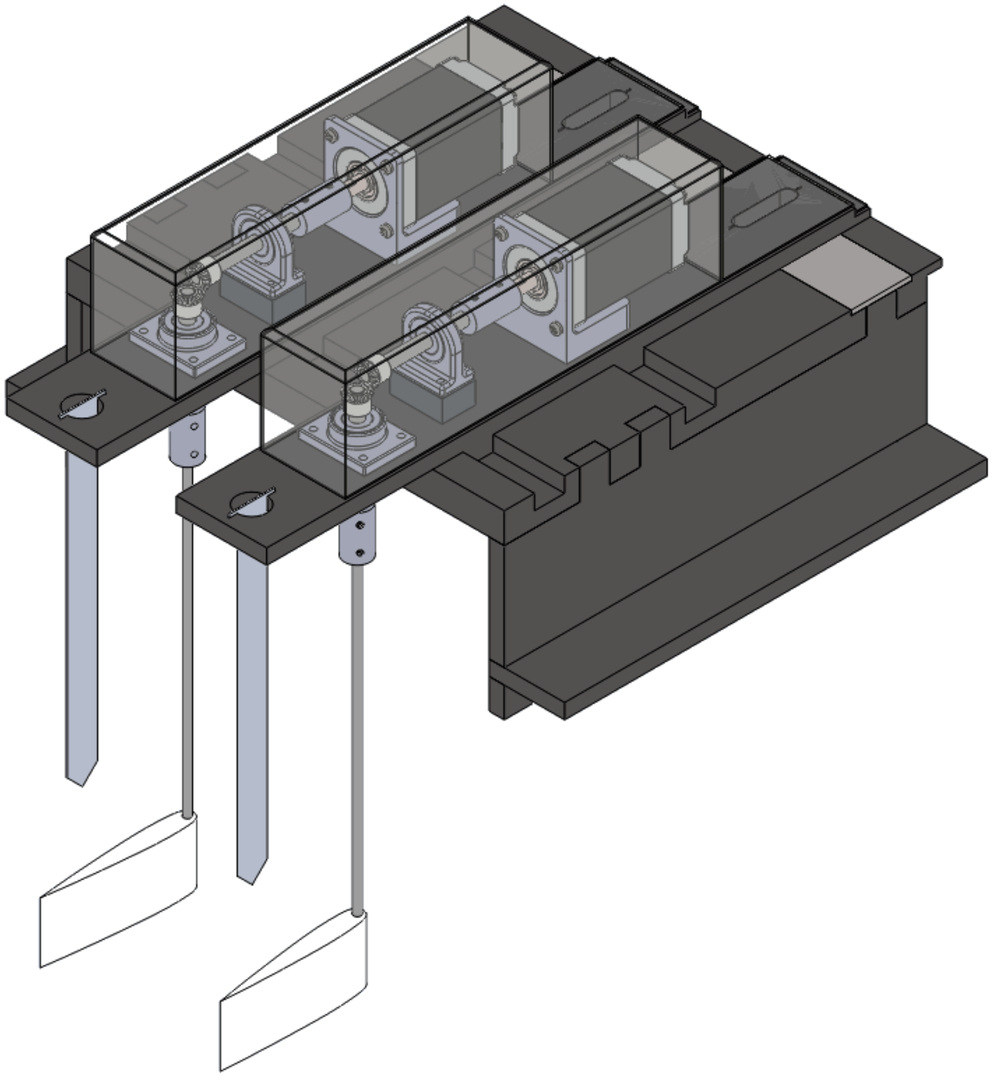


Figure 2. Final design model

The rig is composed of four main subsystems:

1. Drivetrain
2. Baseplate and Motor Planks
3. Locating Tool
4. Flipper Mounts

The drivetrain consists of bevel gears driven by NEMA 11 stepper motors, supported by bearings in their respective housings. The drivetrain sits on two “motor planks” which slide across the baseplate in machined slots, helping laterally position the flippers. The locating tool is a removable device used to initially position the flipper in the 0° position before testing. The flippers are epoxied to shafts and attached to a coupler above the surface of the water

Figure 3. Electronics in the project box

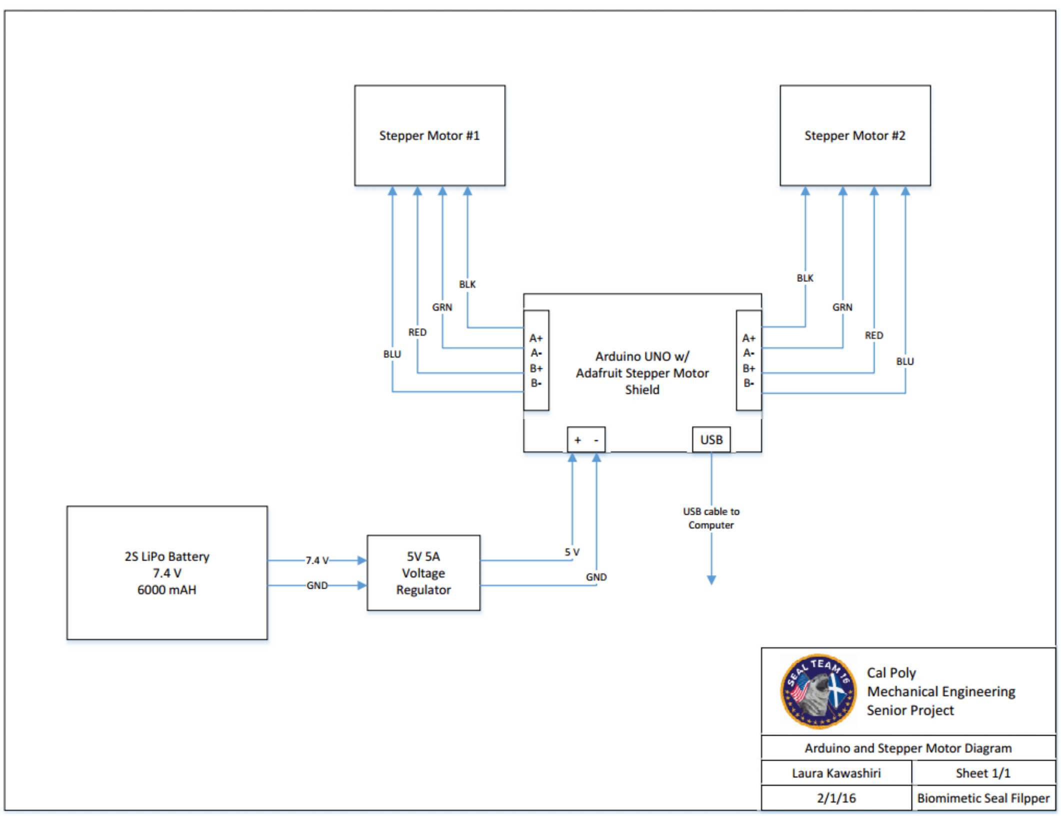


Figure 4. Wiring Diagram

3. Installing a 'flipper'
   Take one 1/8' brass shaft piece and glue it to your flipper using waterproof epoxy (recommended: xxx). Refer to epoxy manual for specific directions.
   Check for cyclindricity between the shaft and the flipper hole
   Allow 24hr to set and cure
   After cure process, install onto 1/8" to 5mm shaft coupler using 3/32" hex key.
4. Code basics
   The motors are controlled with an Arduino and an Adafruit stepper motor shield. User inputs can change the frequency, stepping style, and sweeping distance of each flipper

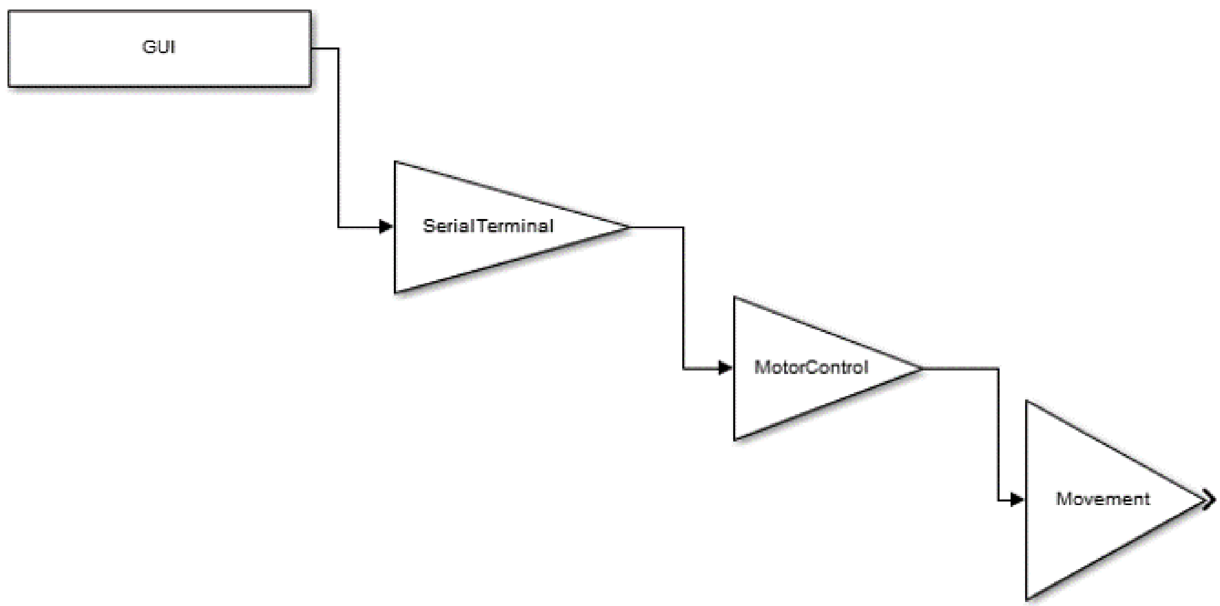


Figure 5. Basic coding flowchart from GUI inputs to movement

5. Running code
   a. To send serial commands to the device, the user must type a command string into the serial monitor command box, located at the top of the window left of the "Send" button in the Arduino interface.

   b. Before sending commands, be sure that the drop-down menu box second from the bottom right corner of the monitor is set to "Newline".

   c. The following example illustrates the command string structure:

      ```
      1R 60
      ```

   d. The first character indicates which flipper to command. Type "1" to control the flipper labeled "Flipper 1", "2" for "Flipper 2", or "3" to change the same parameter for both flippers at once.

   e. The second character indicates which parameter the user wants to change. Options include "E" to enable a flipper, "R" for range of motion in degrees, "F" for frequency in RPM, and "S" for stepping style.

f. The following characters define the new value of the parameter to be changed. They are not necessary for enabling, so the enable command ends after typing "E". The other parameters, however, require a new value**. Be sure to have a space between the second character and the new value characters otherwise the command will not be executed.**

g. For "R", the new value can be any integer between 0 and 100 degrees. Example:

`2R 25`

Translates to "change Flipper 2's range of motion to 25 degrees".

h. For "F", the new value can be any integer between 0 and 200 RPM. Example:

`3F 130`

Translates to "change both flipper frequencies to 130 RPM".

i. For "S", there are four stepping style options:
   i. M = MICROSTEP; smoothest and most refined option that allows for steps less than 1. Tradeoff is lower speed and torque.
   ii. I = INTERLEAVE; alternates between single and double to improve resolution but at half the speed. Still faster than microstep, but more vibrations.
   iii. S = SINGLE; powers one coil at a time to get step-by-step resolution. Decent speed and torque, but noisy with much vibration.
   iv. D = DOUBLE; powers both coils at once to get maximum torque and speed, but with poor resolution and the greatest vibration and noise.

Example:

`1S M`

Translates to "change Flipper 1's stepping style to microstep".

6. Experimental procedure
   a. Ensure battery is fully charged using a LiPo approved charger.
      i. **Never charge above 1 C (5000mAh = 5 amps max charge!)**
      ii. **Charge in provided fire-safe bag**
   b. Check all hardware for proper torque.
   c. Ensure shafts spin freely and that they are not bent
   d. Replace any defective components (see report for BOM).
   e. Install a slipper/shaft assembly on to each motor. Install only one flipper/shaft assembly if only one is required for the test.
   f. Position the flipper and locate using the locating tool.
   g. Power switch off
   h. Plug in battery
   i. Power switch on
   j. Attach USB to computer and start *serial command*
   k. Serial command stuff
   l. Etc….
   m. Unplug battery and low voltage alarm after use. DO NOT let LiPo battery drop below 3.0 volts per cell. Use a low voltage alarm/auto
7. Maintenance and Repair
   a. Keep shafts well-oiled to resist corrosion.
   b. Clean the rig periodically to ensure dyes and chemicals do not corrode the rig.

c. Make sure the battery is charged and does not ever drop below 3.0 V per cell.
d. All tools needed to remove and replace parts on the rig are supplied with the tool kit.
e. Spare parts such as bearings, gears, stepper motor, and bolts/nuts are also supplied.
    i. Additional parts may be ordered off the BOM available in the final report.