Marine Gastrobot Final Design Report

College of Engineering
Mechanical Engineering Department
California Polytechnic State University, San Luis Obispo

Sponsor: Dr. Christopher Kitts,
Director of the Cal Poly Center for Applications in Biotechnology

Prepared by:
Ocean Locomotion

Eric Dreischerf
edreisch@calpoly.edu

Wesley Williams
wewillia@calpoly.edu

Tommy Yath
tyath@calpoly.edu

June, 2017

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Acknowledgements

Advisor: Dr. Peter Schuster

Sponsor: Dr. Christopher □itts

With thanks: MFC Development Team□□ohn Contovasilis□□esse Tambornini□□ohn Gerrity□Charlie Refvem□Ma□ Selna□David Ba□er□Tom Moylan□□ason Felton□Cal Poly Pier

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2 EXECUTIVE SUMMARY

The marine gastrobot sponsored by Dr. Christopher Kitts of the Cal Poly Center for Applications in Biotechnology was a research and development effort intended to explore the use of microbial fuel cell technology as a power source for underwater robots. Our team Ocean Locomotion succeeded in developing a first iteration of an underwater robotic platform suitable for microbial fuel cell integration. The primary feature of the design is its sinusoidal fin propulsion intended for benthic exploration with limited risk of entanglement.

During the course of development, Ocean Locomotion explored the use of low power actuation methods and determined their limited use for underwater locomotion, tested low power boost converter compatibility with microbial fuel cells, and built hardware capable of integration with microbial fuel cells.

Future efforts in development should include further exploration in the power electronics aspect of energy harvesting from microbial fuel cells. Moreover, a few key changes should be made to improve the efficiency of the mechanical system propelling the robot. Lastly, additional work should be done in creating a method of emptying and replenishing food supplies for the bacterial colonies within the microbial fuel cells.

3 INTRODUCTION

The Cal Poly Center for Applications in Biotechnology wanted to explore uses for microbial fuel cells (MFCs) with a secondary objective of promoting long-term interest in the Cal Poly Pier. Our team Ocean Locomotion was tasked with designing a product that fulfilled this need. Our goal was to design a vehicle that could use energy from microbial fuel cells to explore marine environments and provide a platform for further development by interdisciplinary teams of students and researchers.

The remainder of this document details the background research used to understand the challenge, the specifications and objectives of the project, the design and manufacture of this marine gastrobot, and the results from testing of the system. A bibliography and attachments are also provided for reference purposes following the conclusion of the report.

4 BACKGROUND

This section describes the customer needs for a marine gastrobot, explains how the relevant technology works, and discusses existing products related to the goals of this project.

4.1 The Customer

Because of customer development efforts, three groups were identified as stakeholders in our project's outcome: Dr. Kitts, students and researchers at our university and others abroad, and the Cal Poly Pier. While many of the needs of one group overlapped with those of another, a few differences did exist among those interested in the marine gastrobot. Refer to the Venn diagram in Figure 1 below to understand the needs interactions of the various groups.

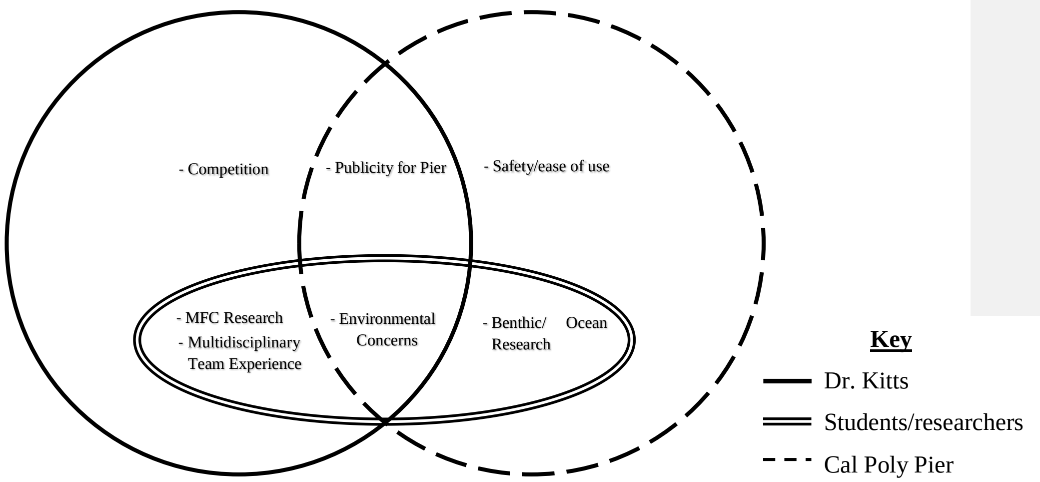

Figure 1. Diagram Depicting Interaction of Various Stakeholder Needs for Gastrobot Project.

4.1.1 Dr. Christopher Kitts

Dr. Kitts is our sponsor for the gastrobot project. He is primarily interested in microbiology, especially in the use of microbes to generate energy as demonstrated with MFCs. He has recently returned to research after eight years of serving in an administrative role as the chair of Cal Poly's biology department. MFC technology is a relatively unexplored field for Dr. Kitts, but one where he hopes to direct his research endeavors in the future. He would like to see more students get involved in MFC research and hopes that a marine gastrobot competition would bring interest to this field, while simultaneously generating interest in Cal Poly's Pier and fostering multidisciplinary collaboration among universities.

4.1.2 Students/Researchers

This stakeholder is the end user for the marine gastrobot platform. Students and researchers are expected to build upon the technology developed during this senior project to improve the design and/or tailor the underwater platform to their unique scientific goals. This group represents our target demographic for future marine gastrobot adoption and has long-term interests in benthic/ocean monitoring and research.

4.1.3 Cal Poly Pier

This stakeholder is the organization that regulates pier use at Cal Poly's pier in Avila Bay. This group is primarily interested in marine research and wants to ensure the Pier is a safe, environmentally-friendly educational resource. The Pier would benefit from additional publicity and attention from groups beyond the marine science community.

4.2 The Technology

This section describes the key technology necessary for a marine gastrobot. An overview of electrochemistry, especially as it relates to microbial fuel cells, is presented along with a discussion of MFC types and their associated challenges. Lastly, propulsion methods are introduced to understand the numerous possibilities that exist for development.

4.2.1 Electrochemistry Overview

Electrochemistry is the science behind electricity production as the result of chemical reactions. Devices capable of producing electricity through chemical reactions are called fuel cells and are governed by fundamental equations of electrochemistry. Refer to Figure 2 below for a diagram of a typical galvanic fuel cell.

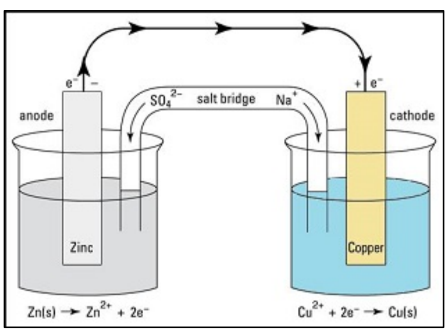

Figure 2. Diagram of a Typical Galvanic Cell. [1]

Galvanic cells typically have four components: an anode, a cathode, a salt bridge, and an electrically conductive material for current to flow (typically a standard copper wire). In the diagram above, the anode is an aqueous solution of zinc sulfide ($ZnSO_4$) connected to an aqueous copper sulfide ($CuSO_4$) cathode solution via a sodium sulfide (Na_2SO_4) salt bridge and a wire.

Solid zinc is attached to the wire and suspended in the zinc sulfide solution; similarly, solid copper is attached to the other side of the wire and suspended in the copper sulfide solution. This chemical configuration is very like that of a microbial fuel cell and both systems operate under similar conditions.

4.2.2 MFC Types

Microbial fuel cell types are of two main varieties: sediment-based and liquid/liquid exchange. All microbial fuel cells utilize electrochemical reactions to generate power. MFCs consist of an anode (typically under anaerobic – without oxygen – conditions) and a cathode (typically under aerobic – with oxygen – conditions), physically separated in space. Oxidation – or loss of electrons – on the anode side and the resulting affinity of the cathode side for reduction – or gain of electrons—causes a flow of current when the two sides are connected as a galvanic cell. The magnitude of this flow of electrons corresponds to the energy produced by a microbial fuel cell, and is typically measured in units of W/m^2 indicating the energy produced per unit time relative to the size of the anode or cathode surface area.

4.2.2.1 Sediment MFC

This variation of MFC uses organic matter available in sediment as its source of fuel. Hydrogen (H^+) ions released during the oxidation of organic material and water (H_2O) on the anode side create an imbalance of positive ions in the soil. These free hydrogen ions then interact with microbes naturally present in the soil to facilitate a reduction half-reaction at the cell's cathode [2]. When a resistive load (a motor, for example) is connected between the buried anode and exposed cathode, a current can be measured.

4.2.2.2 Liquid/Liquid Exchange MFC

Liquid/Liquid exchange MFCs resemble a more typical fuel cell, with physically separated aqueous anode and cathode solutions. This physical separation is generally achieved using a proton exchange membrane (PEM) that permits positive hydrogen ions (H^+) to diffuse from the anode region to the cathode region. The anode solution hosts colonies of electricity-generating bacteria that form what is known as a biofilm. The bacteria of the biofilm (often from the genus *Geobacter* [3] or *Shewanella* [4]) generate electricity by separating electrons from hydrogen atoms

Commented [EKD1]: Will talk to Dr. Kitts to make sure this description is accurate in a reaction known as oxidation, releasing positive hydrogen ions (H^+) in the process. These hydrogen ions are transported by chemical mediators (often potassium ferrocyanide) to the PEM for diffusion into the cathode side of the MFC. A reduction reaction involving hydrogen ions and oxygen takes place in the cathode solution producing water (H_2O) as a result.

4.2.3 MFC Rover Technical Challenges

Creating a robotic vehicle to run on microbial fuel cell power comes with a number of challenges that need to be addressed. Those technical challenges include power management, chemical reaction byproduct utilization, propulsion, communication, and self-sufficiency.

4.2.3.1 Optimizing Power

The principle challenge for the marine gastrobot project is powering an underwater rover with the limited power output produced by existing microbial fuel cell technology. Direct power output of a single MFC lies in the 100-2000 mW/m^2 range [5] which is capable of powering no more than a few LEDs at a time (requiring around 50 mW for operation). On board energy storage may be necessary to provide sufficient power for operating electronics and providing locomotion. Although the first rover iteration will be rudimentary in design, the more power generated by the fuel cells, the more accommodating our platform will be for future development by teams of students and researchers.

A number of factors contribute to the generation potential of microbial fuel cells. These factors include bacterial composition, membrane material, MFC type (mediator, donor, electron acceptor), and surface area available for ion exchange. A study performed by Purdue University students [6] to construct an MFC with inexpensive materials showed a comparison in power output with their and other MFCs based on internal resistance (summarized in Table 1 below).

Table 1. Comparative power densities with varying internal resistances, adapted from Purdue Student MFC Study Results [6].

	Internal Resistance (Ω)	**Max Power Density (μW/m^2)**	**Membrane Cost ($/m^2)**	**Power per Dollar (μW/$)**
Purdue Student Cell	58,000	48	14	3
Nafion Bottle Cell	1272	38,000	1400	27
Nafion Cubic Cell	84	514,000	1400	367

The Purdue researchers' high internal resistance was due to a Gore-Tex proton exchange membrane. High internal resistance results in lower power output ($P = V^2/R$). Therefore, it would be favorable to find a proton exchange membrane that could balance low resistance with low cost should we want an affordable, high power output microbial fuel cell.

The power output can also be optimized independent of the battery design. Voltammetry sweeps have been performed on MFCs to determine optimal voltage for maximum power output (Figure 3). Various load resistances are subjected to the battery and a resultant voltage and current density are recorded. This peak power output occurs when the battery's internal resistance is equal to the external or load resistance as just described.

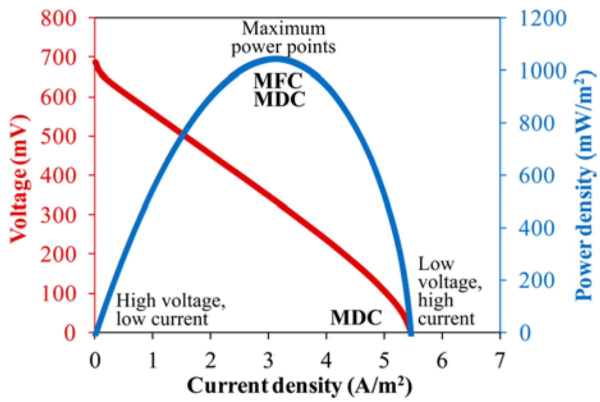

Figure 3. Voltammetry sweep of MFC [7].

There are also other means of attaining maximum power. Because direct MFC outputs are not sufficient for practical applications such as propelling our rover, means for improvisation have been developed through the design of electrical circuits that interface with MFCs [7]. One such means are custom energy harvesting methods. These methods utilize electrical components such as capacitors, batteries, and boost converters to collect, store, and dissipate energy from the low power output of a Microbial Fuel Cell. This approach has potential for great energy yields but would most likely require the expertise of an electrical engineer due to the complexity of the circuitry necessary. Fortunately, there are a few low voltage boost converters that can be purchased for a reasonable price. Figure 4 provides example methods of combining electrical and mechanical components in order to produce energy harvesting methods and circuits.

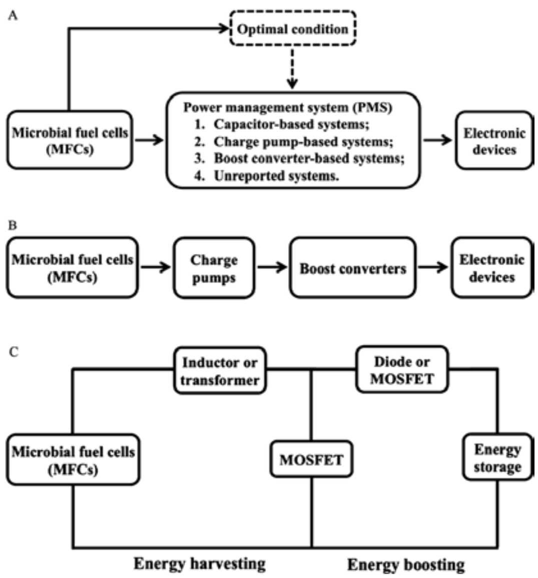

Figure 4. Energy Harvesting Methods for MFC [7].

4.2.3.2 Alternative Energy Use

To our advantage, MFCs generate energy in varying forms. CO_2 and heat generation are also byproducts of the metabolic process which occurs in microbial fuel cells. There is potential for using the CO_2 to control buoyancy or propel the rover underwater. An immediate concern would be the MFC's ability to cope with back pressure if our goal is to store CO_2 byproduct on our vehicle. Little research has been performed on the CO_2 collection from an MFC. Furthermore, the temperature of an MFC may be utilized as a heat source, perhaps allowing fresh seawater to naturally rise, from a heat gradient, through the cathode to provide a constantly refreshed O_2 acceptor source.

4.2.3.3 Propulsion

Challenges also exist in using the generated power to move through the water. Methods of crawling, swimming, slithering, or floating through the water column are all approaches to propulsion but would likely require power beyond levels produced by MFCs. As a reference, MigaMotors are often used for low power applications including solar panel deployment in small-scale satellites. These small actuators still require power on the order of a few watts which would appear to rule out motors of this type from use in a marine gastrobot.

In addition to propulsion power difficulties, the seafloor is an unpredictable obstacle course, making navigation even with unlimited power a challenge. It was therefore decided that propulsion through the water column would be best, but that the rover could rest on the sea floor at intervals to allow for potential recharging, feeding, and waiting for environment turbulences to subside.

4.2.3.4 Navigation

Navigation will most likely be out of the scope of this project. This project's purpose is to prove that an underwater rover may be moved using solely the power of an onboard MFC. Once this challenging objective is accomplished, future versions could integrate navigational systems capable of expanding the MFC rover's capabilities. We chose not to pursue navigation due to the added design complexity of integrating a navigation system and the additional power consumption such a system would require.

4.2.3.5 Self-Sufficiency

The final technical challenge worth addressing is the maintenance of the onboard microbial fuel cell, specifically the feeding and expulsion operations required to support a long-term, self-sufficient cell. Food introduced to the microbial fuel cell anode chamber will deplete after a certain amount of time once the bacterial colony has harvested all energy from the food source. Additionally, waste that is no longer useful must be discharged, similar to that of the human digestive system. There are many approaches to solving this problem. A rover may contain a storage vessel for biomass onboard that constantly feeds food into the anode chamber through gravity, pressure gradients, or powered pumps. Similar means might be used to expel expended waste. The long-term goal of this project is to develop a rover that is self-feeding, thereby negating a need for 'pre-fueling' and allowing the rover to theoretically survive indefinitely and autonomously. Self-feeding can be performed through various means such as suction and filtration of benthic sediment or consumption of suspended biomass in the water column. For this initial investigation, the challenge of developing a self-feeding system is out of the scope of the project at this time.

4.2.4 Means of Propulsion

Propulsion underwater presents both benefits and challenges. A benefit is that propulsion underwater is more independent from the need to overcome the effects of gravity, allowing for more specialized propulsion systems in both mechanical and biological systems. However, there are difficulties in moving underwater, particularly in drag and the inertia of the water that will affect the propulsion systems. To better understand possible design options, a large sample of propulsion techniques were explored.

4.2.4.1 Biological Propulsion

Marine life has evolved several specialized means of propulsion, leading to a wide variety of motion. These mechanisms of propulsion are the most efficient means of underwater propulsion. Due to evolutionary emphasis on creating effective locomotion underwater, often the method of locomotion relates to marine animal body structure.

4.2.4.1.1 Undulation of Body

One of the most common means of propulsion in marine life is an undulation motion of the body, or bending the body in a smooth wave-like motion. In its most basic form, the undulation of the body requires the marine animal to repeatedly bend its body in one direction and then into the opposite direction with the purpose of pushing a body structure against the water. The push against the water causes an opposing thrust force from the water onto the animal that propels the animal in a direction [8]. The variations are based on body structures that are primarily used for pushing against the water. The most common is body caudal fin undulation, or one that uses primarily the tail fin of the fish [9] as the pushing point during body undulation, such as the movements of tuna and sharks. Figure 5 shows how thrust is generated from body caudal fin undulation.

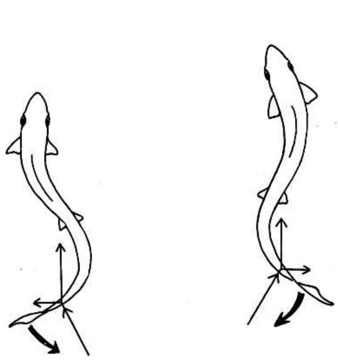

Figure 5. Diagram of body caudal fin undulation of a fish for propulsion. The bold arrow shows direction of tail motion. The diagonal arrow refers to the force vector of propulsion generated by the fin undulation. The perpendicular arrows show the magnitude of the thrust in the x and y directions. [10]

Marine mammals with horizontally oriented tail flukes use a similar undulating motion in a vertical plane of motion. Furthermore, some animals such as eels have a longer fin surface that can have multiple waveforms through its body due to greater flexibility and usage of more of its body length in the motion [11] This concept also extends to rays, skates, and flatfish which undulate their fins to create small thrust that both lifts the fish above the seafloor and propels them forward [12]. Figure 6 shows the undulation of the fins of a stingray for locomotion.

Figure 6. Stingray demonstrating undulation of fin surface for locomotion [13].

In addition to stingrays, cuttlefish exhibit the same fin undulation, but as opposed to using their entire body for the undulatory locomotion cuttlefish have a pair of fins at the side of the cuttlefish head. The pair of fins undergo undulation that provides thrust for the cuttlefish. Figure 7 shows an example of cuttlefish locomotion.

Figure 7. Cuttlefish using paired fin undulation for locomotion [14]

4.2.4.1.2 Median Paired Fin Rowing motion

A fewer number of fish species primarily utilize a rowing motion of their fins to create thrust [9]. The main distinction within this propulsion method is which fins are used. In balistiform locomotion, the dorsal and anal fins, or the fins along the vertical axis of the fish, undergo a circulating motion that generates thrust by pushing water during half of a fin stroke, seen in exaggeration in the mola mola fish [9]. Figure 8 shows the fins of the mola mola used in balistiform locomotion.

Figure 8. Mola mola using exaggerated fins for balistiform locomotion [14]

The other propulsion method is labriform locomotion, which utilizes the pectoral, or side fins in a circulating rowing motion [9]. This technique is often used by fish that are not streamlined, such as pufferfish. Certain ray species such as the manta ray perform a similar oscillating rowing motion with their pectoral fins for locomotion [12], as seen in Figure 9.

Figure 9. Manta ray wing rowing motion [15]

There are non-fish species of marine life that will perform a similar paired rowing motion, such as the use of flippers in the case of penguins [16] and sea lions [17]. A photo of penguins swimming can be seen in Figure 10.

Figure 10. Penguins using their wings to propel forward [18]

4.2.4.1.3 Jet Propulsion

For marine animals without rigid structures that allow for propulsion from a fin pushing against water, propulsion by water jets is a common locomotion method. This method is seen commonly in jellyfish, octopuses, and squids. Jellyfish jet propulsion is performed by the expansion and contraction of the head of the jellyfish in certain jellyfish species. Upon expansion of the head of the jellyfish, water is drawn into the cavity. When the jellyfish contracts its head, the water drawn in during expansion is forced out, providing thrust for the jellyfish [19]. A diagram of this locomotion can be seen in Figure 11.

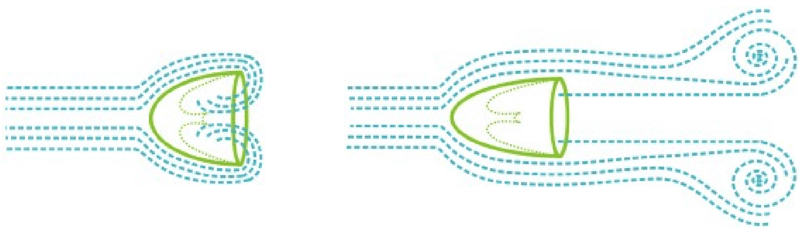

Figure 11. Diagram of water flow during jellyfish jet propulsion [19].

Octopuses and squids have a similar jet propulsion method. Octopuses and squids both draw in water by expanding a cavity located in the head of their bodies. However, instead of contracting the cavity and forcing the water out of the opening of the cavity, flapper valves close the opening to the cavity and the water is forced through another opening that acts as a nozzle for the jet [20]. This provides a more powerful and controlled propulsion. The propulsion is graphically represented in Figure 12.

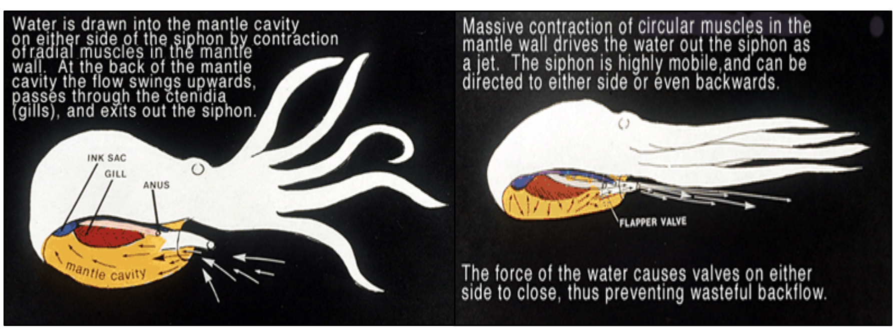

Figure 12. Diagram of cavity and flap actuation that controls octopus jet propulsion [20].

4.2.4.1.4 Crawling

Locomotion underwater is not strictly limited to swimming in the water. Another common locomotion method is to travel along the sea floor. Shellfish such as crabs and lobsters utilize multiple jointed legs to walk across the sea floor [21]. In the case of crabs, their legs have joints with one-degree of freedom, meaning they can only extend and contract their legs in one direction with limited rotation from the joint connecting leg to the body. Because of the nature of their leg joints, most crabs utilize a sideways walking motion where the lead legs pull the crab and trailing legs push [21]. The design of the legs allows the crab to lift its body off the sea floor. Furthermore, a crab can overcome obstacles using its numerous legs and the vertical movements of the legs to find multiple anchoring points and pull up the body to climb up and over the obstacles. There are some species of crab such as the hermit crab and various other tidal crabs that travel in a forward-facing motion, using primarily the front pairs of legs to pull the crab forward. A photo of crabs walking can be seen in Figure 13.

Figure 13. Crabs walking in horizontal direction [22].

Lobsters use a similar locomotion method. Lobsters have four pairs of walking legs that are more spaced apart than in the case of crabs. The spacing between the legs allow the legs to move in a shuffling motion that allows the lobster to crawl forward [23]. Octopuses also utilize a crawling motion across the sea floor. They use their tentacles to either pull and shuffle along the sea floor [24], as seen in Figure 14. In some cases, octopuses will rise on a few of the tentacles and essentially utilize a walking motion with the legs.

Figure 14. Octopus crawling along the sea floor [25].

4.2.4.2 Mechanical Propulsion

To overcome the challenges of travelling both over and through large bodies of water, humans have developed technologies to provide propulsion to vessels and objects that allow users such as divers to travel quickly. There are only a few designs that are widely utilized on vessels, although scientists and engineers are working to produce technology that mimics marine animals and their methods of locomotion.

4.2.4.2.1 Propellers

The most common method of mechanical propulsion is the propeller. Widely used on boats and underwater ROVs, the propeller uses electrical energy to power a motor that spins the propeller. An example can be seen in Figure 14. Because of the shape of the propeller blades, water is pushed away by the spinning motion, providing thrust for the boat [26]. Variations of this design range mostly by source of power (i.e. steam, diesel, nuclear), size of propeller, control of blade pitch and number of propellers. The propeller is a common and effective means of providing locomotion to vehicles. Propeller based propulsion require large amounts of constant power, however.

Figure 15. Propeller attached to a boat [27].

4.2.4.2.2 Jet Propulsion

The other common means of mechanical propulsion is creating jets of water. By using pumps, kinetic energy is added to water entering the jet turbine. The kinetic energy added to the water allows to water to exit a nozzle at a high velocity, providing a thrust force for the vessel [28]. Two examples can be seen in Figure 16. Jet propulsion is generally used in high speed transportation as it produces higher thrust than a propeller. However, it does have much higher power demands to operate the pump.

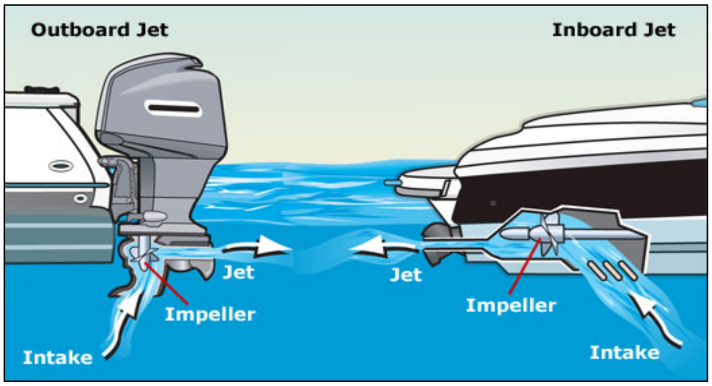

Figure 16. Integration possibilities for jet engines on boats [29].

4.2.4.2.3 Mechanical Marine Animal Mimicry

While propellers and jet propulsion might be the standard for mechanical marine locomotion, engineers are developing technology that mimics biological locomotion as alternatives to traditional methods. A team in Harvard has developed a robot that mimics the undulating motion of a fish using a soft robot [30]. The robot can be seen in Figure 16. The majority of the robot was developed using a soft silicon body that encases a hard case center. The hard center drives a pneumatic system that forces air through channels in the body that causes bends motion similar to a fish's undulation motion. A team in Italy has developed a soft robot that mimics both the crawling and jet propulsion of an octopus. The robot named the PoseiDRONE, implements a soft head cavity that creates a jet propulsion in nearly an identical method to an actual octopus [31]. The PoseiDRONE also employs its soft tentacles to utilize a rapid shuffle to mimic the walking locomotion an octopus can employ. The PoseiDRONE using both methods of locomotion can be seen in Figure 17.

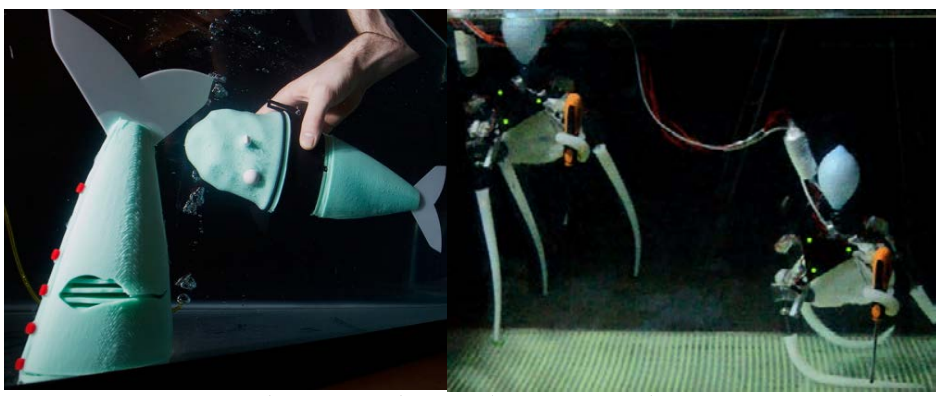

Figure 17.Two examples of mimicry: Soft bodied fish mimicry (Left) [30], PoseiDRONE (Right) [31].

Another project that performs marine animal mimicry for propulsion is the Sepios underwater ROV from the Swiss Federal Institute of Technology. The Sepios robot uses 36 servos to actuate four wings in an undulatory motion, mimicking the cuttlefish. The four wings are controlled and actuated in a manner that allows for omnidirectional motion. The Sepios ROV can be seen in Figure 18.

Figure 18. The Sepios ROV mimicking cuttlefish locomotion [32]

4.3 The Product

To understand the complexity of this project, sufficient benchmarking needed to be performed. Ocean Locomotion chose to separate its research into two main areas focusing on 1) microbial fuel cells and 2) underwater vehicles.

4.3.1 Use Cases

After gaining an understanding of the chemistry governing MFC design, Ocean Locomotion investigated existing use cases for this unique form of energy harvesting. Research revealed four novel areas of microbial fuel cell application: wastewater, breweries, urine, and remote sensing.

Microbial fuel cells feed on organic matter in order to generate electricity. Municipal wastewater can be used as a steady supply of food for MFCs, with the added benefit that the MFC usage cleans the water and produces power usable by the treatment plant for further operations [32].

Breweries employ MFCs in a manner similar to that used by wastewater treatment plants cycling untreated water past microbial fuel cells in order for reduction-oxidation reactions to occur.

The beer manufacturer Foster's uses this technique in its brewery in Brisbane, Australia to clean wastewater from the brewing process and generate electricity as a byproduct [33].

Another novel approach along the lines of waste treatment is the use of urine as a fuel source for these cells. A team from the Bristol Robotics Lab in England demonstrated that human urine in combination with a specially designed MFC could produce sufficient power to charge a cell phone [34]. The results of this study seem to suggest that useful energy densities can be harnessed from MFCs and that more typical applications for this power source might soon be on the horizon.

The final case study researched was the most similar to the type of project requested of our team, a design for a benthic microbial fuel cell (BMFC). The Naval Research Laboratory developed a type of BMFC for extended deployment that was capable of powering sensors for monitoring and communication [35]. These Benthic Unattended Generators (BUGs) were submerged into sediment of the ocean's benthos and produced electricity reliably and cleanly. Unfortunately, these BUGs remained stationary on the seafloor, incapable of relocating or self-feeding should environmental conditions change.

4.3.2 Underwater Vehicles

After gaining a sufficient understanding of the theory governing MFCs, Ocean Locomotion chose to benchmark our project's goals against existing underwater vehicle solutions. Research revealed that scientists typically use expensive equipment for exploring the ocean, including Autonomous Underwater Vehicles (AUVs) [36]. Some AUVs are capable of diving to extreme depths but are limited by battery life in terms of how long individual missions can last. Other AUVs (such as the WaveGlider, Figure 19 below) are surface-based, harvesting renewable energy from wave action and from sunlight [37].

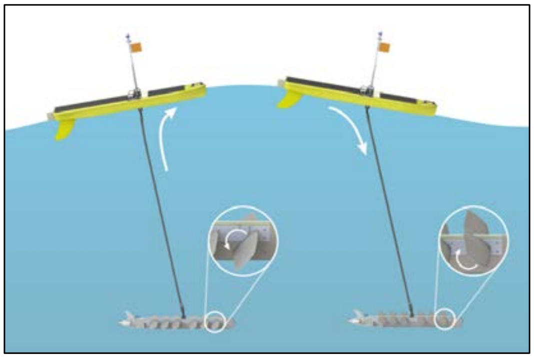

Figure 19. Illustration Depicting Functional Technology of Wave Glider AUV [37].

Unfortunately, these designs also have limitations since surface-based AUVs are unable to explore the benthic region of the ocean due to their need to be on the surface of the water. Regardless of the type of AUV, it was also the case that this marine technology was not available for widespread use by most university-level programs, either due to cost, complexity, or lack of versatility.

Ocean Locomotion then investigated low-cost solutions for underwater exploration. The OpenROV (Remotely Operated Vehicle, Figure 20 below) was one such platform that revealed itself to be affordable (~$900), versatile (completely open source), and capable (300ft depth rating) [38].

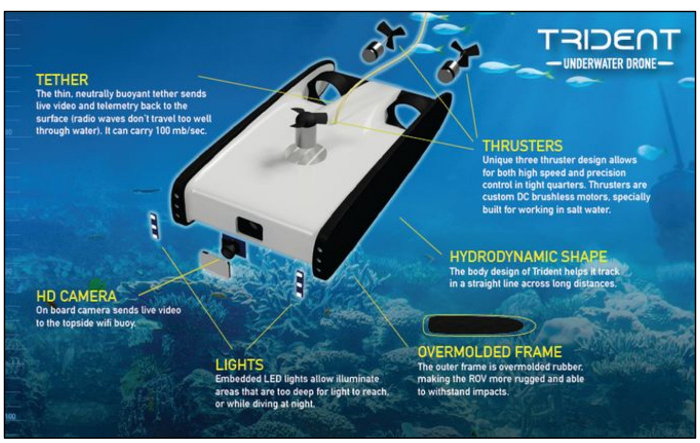

Figure 20. Product Description of Commercially Available OpenROV [38].

A major drawback to this design was its tether, required for powering and communicating with the vehicle. This feature effectively limits the range of the ROV, preventing long-term, unassisted deployment due to the need to be tethered to the surface.

Lastly, benthic robots were studied. One robot seemed applicable for our project's goals, the Benthic Rover shown below in Figure 21.

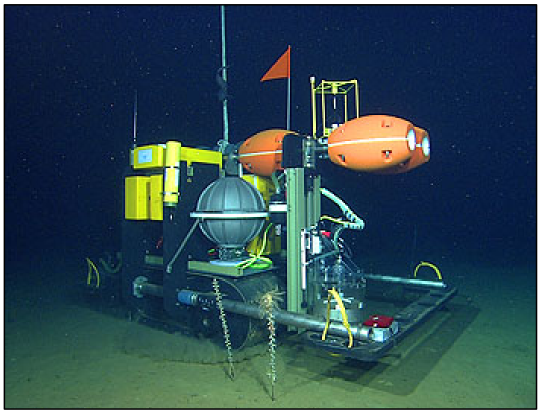

Figure 21. Benthic Rover Used by MBARI for Oceanographic Research [39].

This vehicle used by the Monterey Bay Aquarium Research Institute (MBARI) was designed for long-term benthic ocean research [39]. This design is well-tailored for benthic exploration, but unlike the OpenROV, is custom-made and orders of magnitude more expensive.

5 DESIGN REQUIREMENTS AND SPECIFICATIONS

Our project goal is to deliver a fully functioning underwater remotely operated vehicle (ROV) that will be powered by a MFC or by using a battery with comparable power output. It is intended to be operated along the proposed race course from the Cal Poly Pier in Avila Bay towards Olde Port Beach. When we initially received the project, we went through a period of developing a project scope that we could accomplish in the 9-month period of senior project. This endeavor began by creating a boundary sketch that allowed us to focus on what we would want to design without irrelevant influences outside of our control. The boundary sketch can be seen in Figure 22 below. As seen in the boundary sketch, the circle is around the characteristics of the problem that we can control and solve.

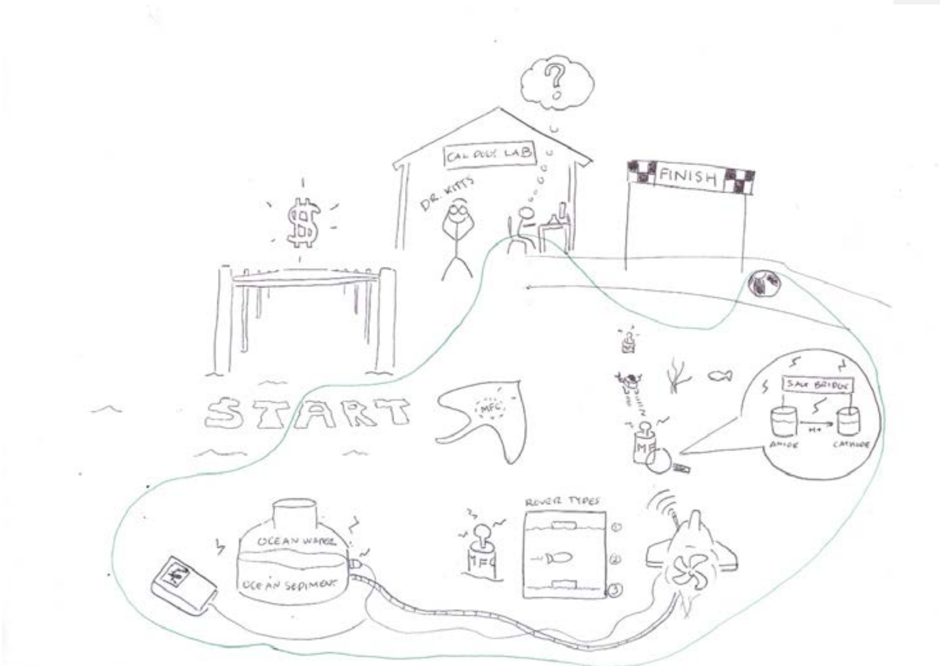

Figure 22: Boundary Sketch for the Marine Gastrobot Project

The boundary sketch reduced the project scope to designing a product that will go underwater and integrate an MFC as opposed to designing a fully functional ROV with an onboard MFC that would go the full kilometer along the pier. Our project scope is intended to take an initial step toward this challenge by designing a platform that will both move underwater and integrate MFC arrays that may be built by later Cal Poly groups. After discussion with Dr. Kitts, our project scope was reduced to making a neutrally buoyant ROV that can interface with the different MFC designs. Furthermore, the ROV design will not need to consider methods of refueling or sustaining the MFC beyond access to seawater. The ROV is now assumed to only be operated in testing conditions, with considerations and suggestions for future designs to be used in the pier environment.

Our design specifications for the gastrobot based on the sponsor's and intended users' requirements were created utilizing the Quality Function Design (QFD) method. The QFD method identifies the users of the product, lists their needs for the capabilities of the product and compares them to our predicted design specifications. By rating the correlations between the users' needs and our predicted design specifications, the QFD rates the importance of the design specifications, allowing us to eliminate specifications that would only add unnecessary restrictions. To both numerically and graphically represent the QFD method, an Excel spreadsheet representing our analysis of the users' needs and how we developed the corresponding design specification was created and can be seen in Appendix A.

While going through the QFD process, we compared user requirements such as "good mobility", "modularity" and "ease of deployment" to design specifications such as "speed", "mobility" and "cost". The comparisons were given correlation strength ratings such as "strong", "weak" and "unrelated", denoted by the shapes or lack of. For example, the correlation between "speed" and "good mobility" would be given a correlation of "strong" since excessive speed can limit the mobility of the robot. From the collective correlations of the user requirement to the specifications, the QFD spreadsheet gave a technical importance rating and weight in the How Much box at the bottom of the spreadsheet.

After considering the top technical importance rated specifications designated by the QFD, we identified several specifications as the design features we chose to quantify the success of our design. In Table 2 below, we complied the specifications we will test, the target goals that will quantify success as well as the testing procedures in the form of a compliance method. Any target value for the specifications in square brackets represent values that are currently tentative values that will likely change once we have a better grasp upon what the design more realistically will be capable of.

Table 2. Gastrobot ROV Engineering Specifications.

Spec #	Specification Description	Target (Units) [tentative]	Tolerance	Risk	Compliance
1	Power Output	[500µW]	Min	H	I, T
2	Food Source	Sustainable for 1 week	Min	M	T, S
3	Mobility	[6in]	Min	M	I, T
4	Power Consistency	Steady for 1 week	Min	M	A, T
5	Speed	[0.1mph]	Min	L	T
6	Oxygen Intake	Resupply ocean water every [12 hours]	Min	M	I, T
7	Structural Durability	Leak-proof to 30ft (2atm), 1 month corrosion resistance	Min	L	A, I, T
8	Lifespan	[1 week]	Min	M	T, I

The compliance method is given by one or more of the following: Analysis (A), Test (T), Similarity to Existing Design (S), and Inspection (I). Analysis means testing done through closed-form hand calculations or numerical analysis on a computer program, such as finite element analysis of a component of the chassis of the ROV or by solving closed-form equations by hand. Test implies a practical test such as placing part of the outer material in ocean water to test for corrosion resistance. Similarity to Existing Design implies that we would use either a scaled system or a comparable material of an existing product that has done published testing results. Inspection is a less formal testing procedure that is observing clear failure in a test procedure such as observing if seal failure occurs at conditions at the sea floor by the pier. Furthermore, there is a risk rating of High (H), Medium (M), or Low (L) which is an assessment of the chance of failure in achieving the design specification.

Of these specifications, we found that the biggest constraint will be designing a ROV with power consumption that will be supplied by the low power output MFC. The critical components of the ROV including propulsion, sensors, control, and sustenance of the MFC ecosystem will all rely on some degree of electrical input, meaning power management will be the highest level of risk in our design. From our research into our competition in sediment MFCs and other MFC powered robots, we found that a reasonable power output from the MFC will be 500 μW. The testing of the power input and consumption will consist of measuring the power output of a MFC designed by the Microbiology team assuming their MFC is completed before critical design choices. This will be followed by operating the ROV at this power input for 5 minutes while observing for failure of subsystems.

Other design specifications include sustained food source for the MFC, mobility, power consistency from the MFC, speed, oxygen intake, structural durability, and lifespan, as described in the following list.

- Sustained food source (Specification 2) refers to the design requirement to make sure that the microbes have a food source to be healthy and engage in ATP production, the basis for how an MFC produces power. This requirement means we will need to design either a way to refresh the food source or maintain a food source that will last the test period.
- Mobility (Specification 3) is an essential part of the ROV being able to navigate through the ocean, being able to maneuver around obstacles. As we are aware that we will not have enough power to perform long duration maneuvers, we find that we have done well if the ROV can maneuver a few inches.
- Power consistency (Specification 4) specification refers to have a consistent power output from the MFC which we control by maintaining a consistent and optimal environment for the MFC, fulfilling food source replacement, maintaining oxygen levels, waste management, etc. This specification quantifies how well we maintain our MFC.
- Oxygen intake (Specification 6) specification refers to how well we are supplying oxygen to the cathode for the reduction process to create electricity, a vital component to the MFC. This will be done primarily by replacing a water supply, thus leading to the specification of resupplying the ocean water within a period.
- Speed (Specification 5) will characterize how creatively we managed the power budget for propulsion. As the ROV has low power input, a relatively fast speed of around 0.1 mph when operating will show the efficiency in our propulsion method where the traditional method of propellers will fail.
- Structural durability (Specification 7) is defined by our ROV's need to have a sealed environment for the electronics in a durable chassis that resists corrosion in sea

water and the pressure if we choose to operate closer to the sea floor. Should the chassis fail, the major components operating the ROV will be destroyed.

- Lifespan (Specification 8) refers to the need to produce a robust system that at the very least will perform without major failure to key subsystems for an appreciable amount of time to prove that MFC is viable for these conditions. The future direction in our opinion for the gastrobot is to be a long term self-sustaining and autonomous exploration robot.

Amendments to the Specifications

Because our project scope has changed significantly since when we started, our design specifications needed to change. Originally, our design specifications had been largely based on maintaining the life and overall performance of the MFC, such as oxygen intake or power consistency. However, the MFC team developing the fuel cell has created their prototypes and designs without using ocean sediment as the fuel source. Since their MFC development has not advanced as far as we initially anticipated, our team and our sponsor decided to change our project scope towards focusing only on creating an ROV that will move when powered by an MFC. This change allows our prototype specifications to instead focus on ROV propulsion. As such, our new specifications are based on our current propulsion method of fin wave propagation. The new specifications can be found in the following table.

Table 3. Amended Gastrobot ROV Engineering Specifications

Spec #	Specification Description	Target (Units)	Tolerance	Risk	Compliance
1	Distance Travel per Cycle	1in	±0.5	H	T
2	Speed	0.1mph	Min	L	T
3	Cost	Overall cost of design be less than budget of $4,300	Max	M	I
4	Leak Proof	No water damage to electronics	Max	M	I
5	Cycles per Discharge	4 cycles	±0.5	L	T

Of these specifications, we found that the specification with the highest difficulty to reach and the most critical to our overall design success will be the distance traveled per cycle. Our design is highly dependent on achieving sufficient travel per cycle of the wing actuation since the overall time of actuation may be short. Furthermore, we cannot be certain that our locomotion method of producing a sinusoidal wave in the wings through a crankshaft with rockers is a viable option to producing forward travel when compared to the Sepios robot, which produced a travelling wave through a controlled sequence of servo actuation. This will be tested by operating the ROV in a test tank for one discharge of the capacitor while recording the operation. After the test, we will analyze the video to find how far the ROV travels on average per wing actuation cycle.

Other design specifications include sustained food source for the MFC, mobility, power consistency from the MFC, speed, oxygen intake, structural durability, and lifespan, as described in the following list along with their corresponding testing procedure. The number of the following the specification refers to the specifications number in Table 2.

- Speed (Specification 2) will characterize how effectively we managed the power budget for propulsion. As the ROV has low power input, a relatively fast speed of around

0.1 mph when operating will show the efficiency in our propulsion method where the traditional method of propellers will fail. Speed will be measured by operating the robot in a straight line over a set distance in the test tank and measuring the time it takes to go across the distance.

- Cost (Specification 3) refers the overall cost of components for our system. Our design should not exceed the $4,300 budget we have from a combination of our sponsor's given budget and funds from CP Connect. Included in the budget will be costs for testing equipment and materials for redesigns or repairs if time permits. This will be a running measurement, tracking over purchases, and referring to the remaining budget before making purchases.
- Leak Proof (Specification 4) refers to how water tight our design is at critical areas. These critical areas include the motor housing and the container for the boost convertor circuit. If the ROV were to let water in at these areas, the ROV is likely to be damaged and require replacement parts. This specification will be tested by operating the ROV through multiple discharge cycles while submerged in the test tank. This will continue until failure or we reach a high number of discharge cycles. In this scenario, we will remove the ROV from the test take and open the critical areas, inspecting for the amount of water that may have entered.
- Cycles per discharge (Specification 5) refers to the number of cycles of the wing actuation we can achieve during a discharge cycle of the capacitor. This specification will characterize how well our transmission can transmit the motor torque into wing actuation. This specification will be tested during the same test as Specification 1 and 2. After a discharge cycle, we will refer to the video we recorded and count the number of wing actuation cycles during the discharge.

6 DESIGN OPTIONS

6.1 Selection Process

In order to select a design for the marine gastrobot, a process of ideation and function concept evaluation was used. By the end of this process, designs which seemed suitable for the objective remained to be scrutinized by further methods.

6.1.1 Ideation

Our design process began first with ideation. Our first session was spent with the dual intent of both starting to put our ideas out while identifying which ideation method works best with our team. The three methods we tried were regular brainstorming, brain writing, and finally SCAMPER. In the regular brainstorming method, we as a team just said our ideas for solving the problem and had a period where we could build on other ideas or put a new original idea down, all while recording the ideas. Figure 23 shows the results of brainstorming for the ideation of method of propulsion.

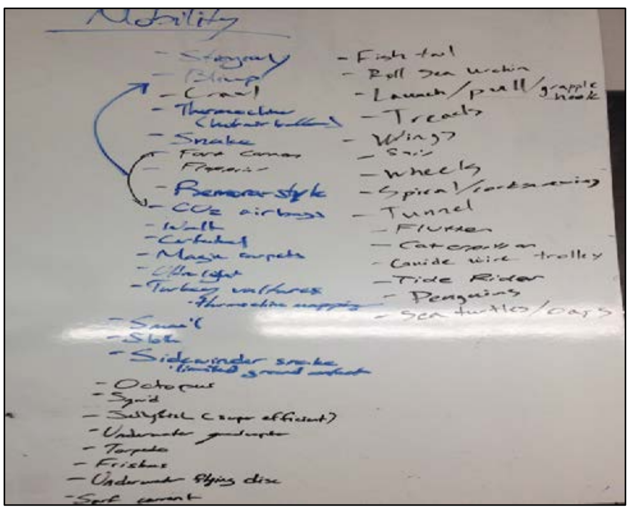

Figure 23. Brainstorm ideation on mobility, the methods of propulsion.

The SCAMPER method utilizes trigger words such as Substitute, Combine, and Adjust which directs our ideas to fit the theme of the trigger word. This was beneficial to use after we were starting to run out of ideas from the brainstorm. Figure 24 shows our attempt at using scamper for the ideation of the structure of the outer shell of the ROV.

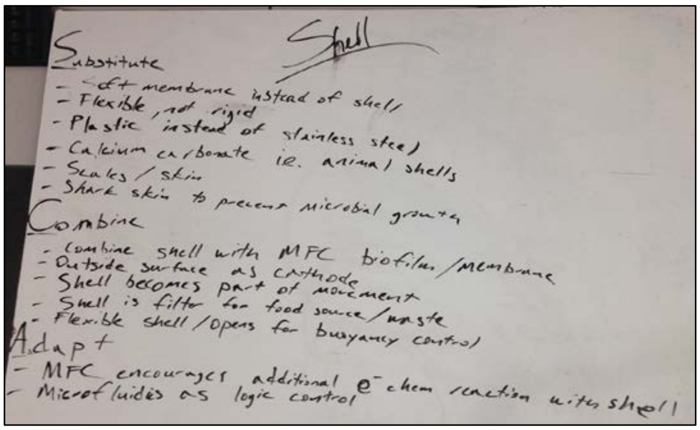

Figure 24. SCAMPER ideation of the outer shell of the ROV.

The final method we used was brain writing. In brain writing, team members individually wrote down ideas on separate papers for a short time period. At the ends of the timeperiode papers were traded and we generated ideas that were inspired what the previous team member wrote. This continued until all team members wrote on the all the papers. Our team found brain writing to be our most effective method of ideation. The following focused ideation sessions were all done using a form of brain writing.

6.1.1.1 Structure Ideation

Our first focused ideation session was for the structure of the ROV. The ideation was focused on the aspects of the ROV chassis such as components integration, component isolation, corrosion resistance, portability, and hydrodynamics. Our team each took a different colored white board marker and wrote down our ideas for the chassis while also labeling each of our ideas under a category for later organization, as well as helping to trigger new ideas, like SCAMPER. After a few minutes, we each followed a different team member's ideas and built on the ideas. This continued for another cycle until we each had the opportunity to build on every teammates' ideas. Figure 25 is a photo of the result of the ideation session.

Figure 25. Brain writing ideation on the structure of the chassis.

6.1.1.2 Overcoming Environmental Challenges Ideation

Our second ideation session focused on overcoming the environmental challenges of the sea floor. This was done after the team participated in a dive clean-up of the sea floor of the Morro Bay dock. Two of our team members dove to benthic levels under the dock, observing comparable conditions to what can be expected at the Cal Poly Pier. The environmental challenges came from difficulty moving in the mud, low visibility, currents, and an unforeseen issue of marine animal interference. The subsequent ideation session was closer to the traditional methods of brain writing, although we assigned each paper being passed around with a specific topic to keep ideas focused but also make each member think of an original set of ideas during each cycle. We found a weakness of traditional brain writing to be repeating of ideas a team member may have already written down on a previous paper. By keeping a specific topic on each paper, each idea written down was original and not replicated in the other brain writing lists. Figure 26 shows the one of the ideas produced for the topic of overcoming the challenges of contaimination. The ideation for the other topics for overcoming environmental challenges can be seen in Appendix A in Attachments 2,3, and 4.

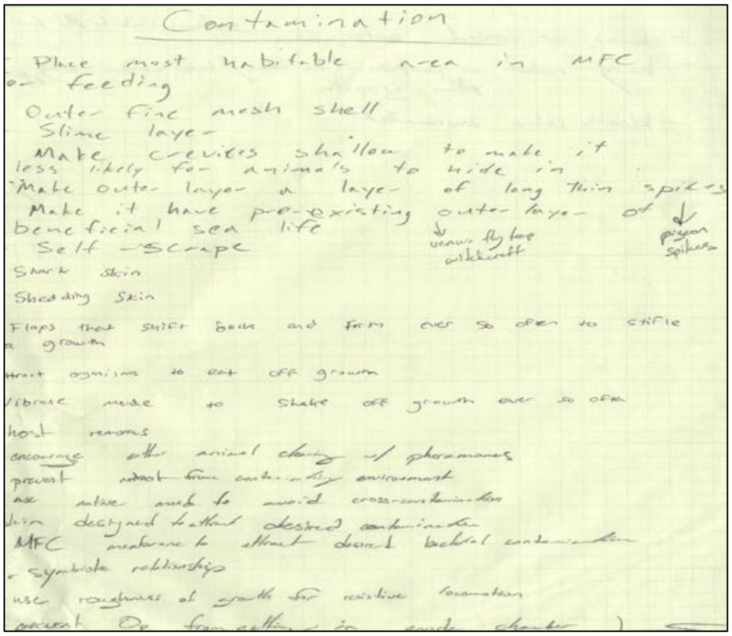

Figure 26. Brain writing ideation on overcoming marine contamination.

6.1.1.3 Propulsion Ideation

Our final ideation session was on the means of propulsion for our ROV. While we have had previous ideation on propulsion, we chose propulsion to be our last focused ideation session because propulsion will dictate much of the design of the other functions and components. We needed to both develop a sense of what propulsion methods were possible with the ideas we had from ideation of the chassis structure and overcoming environmental challenges, as well as become inspired by the previous ideas we generated. For this ideation session, we again used a modified brain writing. As opposed to switching which white board we were writing on, we paused and allowed an individual team member to explain each of their ideas while the other two members wrote down ideas based on the idea explanation. While we lost the opportunity to create new ideas from misinterpretation of ideas, performing brain writing in this method allowed us to create further thought out ideas. Since we already had some preliminary ideation of propulsion, creating more developed ideas as opposed to quantity was a better focus of the propulsion ideation session. Figure 27 shows an initial list of ideas for propulsion by Buck.

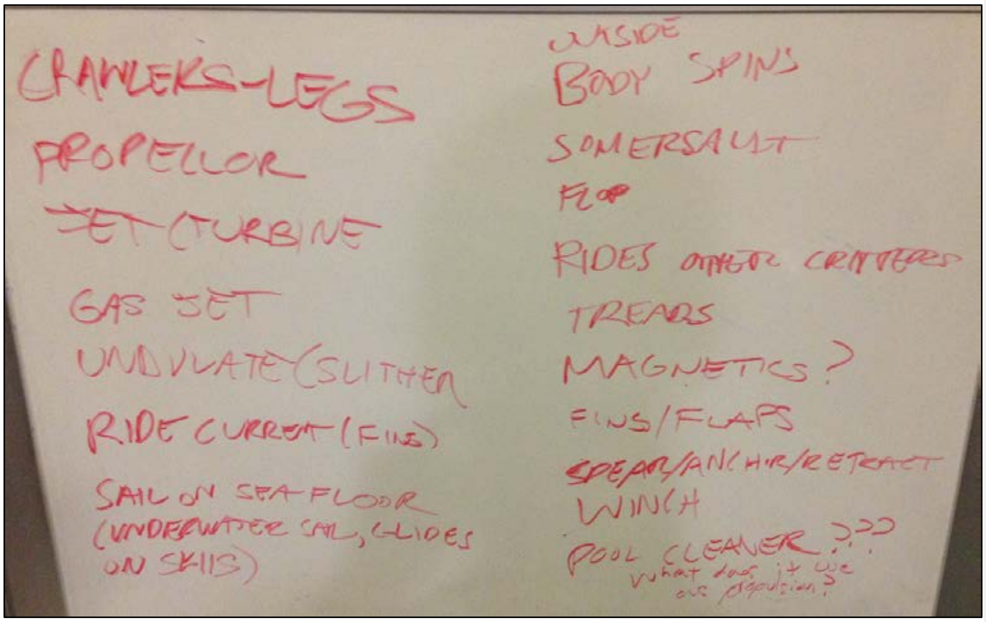

Figure 27. Initial list of Buck's brain writing ideation of propulsion.

6.1.1.4 Physical Model Ideation

After the ideation sessions, we created very basic physical models of some of the concepts. The model building helped us to better visualize how components of the design will come together, as well as help communicate how the concept was visualized during the ideation. This allowed the team to make some preliminary decisions of what concepts could possibly be chosen in the selection process later on. Furthermore, building the concepts helped to inspire new concepts. Figure 28 shows the physical models we created in a three-hour lab period.

Figure 28. 18 physical models of various concepts satisfying functions of the ROV.

6.1.2 Function Concept Decisions

After the ideation sessions, our team went through each of the concepts generated and eliminated ideas we deemed insufficient for the function. The decisions were based on what we as a team felt about the difficulty of implementation, the initial thoughts regarding capabilities and thoughts of overall system integration each concept provided. We continued to eliminate and return to the lists for further reduction until each function had roughly ten leading concepts. At this point, each team member was assigned a function for more rigorous evaluation using a Pugh matrix. A Pugh matrix is an unweighted decision matrix where each concept receives a "same as" (S), "better than" (+), or "worse than" (-) rating when compared to a datum concept for various performance criteria. The datum was what the team member felt was the baseline concept in terms of the criteria. The criteria varied between the functions, but included performance specific criteria such as "impact resistance" for the structure Pugh matrix. After comparing rating each concept, the total number of "+" and "-" where totaled and each concept received a rating of based on the number of "+" the concept received subtracted by the number of "+". This meant positive ratings meant the concept performed better than the datum, giving the team a quantitative reason why the top concepts of each function were chosen. Each team member performed their own Pugh matrix on a function. Buck performed a Pugh matrix on the ideas from “Overcoming Environmental Challenges”, Eric’s topic was “Power Management” and Tommy worked on “Structure”. After each team member completed their individual Pugh matrix, the team came together to ensure ratings were representative of the team’s majority judgement, finalizing the ranking of our concepts. Finally, as a team we performed a Pugh Matrix on the function we felt was the most crucial to do correctly, “Propulsion”.

6.1.2.1 Overcoming Environmental Challenges Concept Selection

The concepts for overcoming environmental challenges were judged on the criteria that included prohibit marine animal growth, hydrodynamics, set-up complexity, reliability, cost, and effects on the environment. The concepts were mostly based on components that would affect the outer layer of the ROV. These concepts include a mesh webbing, hydrophobic coating, creating pre-existing marine life growth on the shell, attracting beneficial marine life and using an electrical anti-fouling system. The datum chosen was using a material or surface texture that would mimic shark skin. With our criteria, most of the concepts generally were rated worse than the shark skin. The hydrophobic coating did match the datum. This lead to the top concepts leaving the Pugh matrix step. The Pugh matrix can be seen in Table 4 below.

Table 4. Pugh Matrix for Overcoming Environmental Challenges

Categories	Shark Skin	Web	Hydrophobic Spray	Pre-existent Growth	Attraction	Anti-Fouling (Electricity)
Resistance to Growth		S	-	-	S	+
Hydrodynamic		-	+	-	S	S
Design Complexity		+	+	+	-	-
Build/Set-Up		S	+	-	S	-
Manhandling	D	S	S	-	S	S
Invasiveness	A	S	-	-	-	-
Reliability	T	-	-	+	-	+
Cost	U	+	+	+	+	-
X-Factor	M	-	-	S	+	+
Sum of +		2	4	3	2	3
Sum of S		4	1	1	4	2
Sum of -		3	4	5	3	4
Score Summation		-1	0	-2	-1	-1

6.1.2.2 Power Management Concept Selection

The power management concepts were the methods we felt could properly harness the low power output of the MFC. These concepts were charging a battery, charging a capacitor, using a boost converter circuit, and parallel MFCs, with the datum being using power directly outputted by the MFC. The criteria included design complexity, the efficiency of the power use, longevity, and the overall usefulness the concept would provide the system. After rating each concept, charging a battery, and using a parallel configuration rated higher than using the power directly. These two concepts moved on as the primary means of power management for the system. The Pugh matrix can be seen in Table 5 below.

Table 5. Pugh Matrix for Power Management

Category	Straight Power	Battery Charge	Capacitor Charge	Boost Converter	Parallel Configuration
Design Complexity	D A T U M	S	-	-	S
Efficiency		+	S	-	+
Usefulness		+	S	+	+
Longevity		-	S	S	S
Sum of +		2	0	1	2
Sum of S		1	3	1	2
Sum of -		1	1	2	0
Score Summation		1	-1	-1	2

6.1.2.3 Structure Concept Selection

The structure concepts were varied. There was not a clear and easy way to compare each concept as they ranged from the structure of the chassis, to features on the chassis and even the material of the outer layer and the chassis. The concepts of chassis structure included tent pole frame, grid frame with an open center, a Nafion or other EAP skeleton, and a structure of air bags and chambers. Features on the chassis included handles, wings, biomimicry skin and Gore-Tex skin. Since all the concepts could be rated by the same criteria, we decided the datum would be an aluminum shell without the features. After rating, each of the concepts, we pulled the top concept from each subcategory of concepts. The top-rated concepts included using handles on the chassis for transportation, a structure of air bags and chambers, as well as a Nafion skeleton. The Pugh matrix can be seen in Table 6 below.

Table 6. Pugh Matrix for Structure

Categories	Aluminum	Handles	Biomimicry skin	Tent Pole Frame	Grid frame open in the middle	Wings	Air Bag and Chambers	Goretex	Nafion Skeleton
Long term Durabililty		S	-	-	S	-	-	+	+
Impact Resistance		S	S	-	-	-	+	+	+
Size-Dependency		-	+	+	-	S	S	S	-
Portability	D	+	-	+	+	-	+	-	+
Cost	A	+	-	+	+	S	+	-	-
Design Complexity	T	+	-	-	-	S	-	S	-
Pressure Tolerance	U	+	S	-	S	S	S	-	S
Sum of +	M	4	1	3	2	0	3	2	3
Sum of S		2	2	0	2	4	2	2	1
Sum of -		1	4	4	3	3	2	3	3
Score Summation		3	-3	-1	-1	-3	1	-1	0

6.1.2.4 Propulsion Concept Selection

The final Pugh matrix was dedicated to selecting the top propulsion concepts. These concepts included mechanical systems such as revolving ski poles, a servo based rotation of legs and a rolling spike design that only allows for one direction of travel. There were systems that relied on environmental conditions, such as utilizing thermal gradients as lift and system of flaps that would catch either currents or tidal movements as a mean of travel. Numerous concepts employed some sort of mimicry of marine life, such as fins, flatfish locomotion, caterpillar crawling and a jellyfish jet propulsion system. The criteria for these concepts power consumption, distance of travel, complexity of design, cost, durability, and terrain adaptability. The datum for the propulsion was using a propeller, the industry standard for ROVs. After rating the concepts, the concepts that performed well were concepts that utilized some form of mimicry including fins and flatfish locomotion, although a system of current catching flaps also scored high. These concepts moved forward for consideration in the system concepts. The Pugh matrix can be seen in Table 7 below.

Table 7. Pugh Matrix for Propulsion

Categories	Propeller	Ski poles/sled bottom	Crab	Clock tick legs	Rolling conical spikes	Caterpillar	Current flaps	Thermal gradient	Fins/Flippers	Flatfish/Magic Carpet	Jellyfish
Power Usage			S	+	+	+	+	+	+	S	+
Distance travel		-	S	-	-	-	-	S	S	S	-
Control Complexity		S	-	S	S	-	S	-	S	-	-
Design Complexity	D	-	-	S	-	-	+	-	S	-	-
Cost	A	S	-	S	+	+	+	S	+	S	+
Durability	T	-	-	-	-	S	S	S	S	+	S
X-Factor	U	+	+	S	+	+	+	+	+	+	+
Terrain Adaptability	M	-	+	+	-	+	-	-	S	+	+
Sum of +		1	2	2	3	4	4	2	3	3	4
Sum of S		3	2	4	1	1	2	3	5	3	1
Sum of -		4	4	2	4	3	2	3	0	2	3
Score Summation		-3	-2	0	-1	1	2	-1	3	1	1

6.2 Decisions from Specifications

The top concepts from each of the Pugh matrices were combined into seven system level design ideas. These ideas were named based on their method of propulsion, a factor that often-dictated power requirements and influenced the vehicle's structure and shape. The seven designs were Stingray with Electroactivated Polymer (EAP) Fins, Current-driven ROV, Flounder Fin ROV, Propeller Submarine, Impeller Open-Center ROV, One-directional Benthic Rover, and Stingray with Nitinol Fins.

To evaluate these ideas, a system level decision matrix was created. In this matrix, engineering specifications were used as evaluation criteria and assigned a specific weight, as determined by the Quality Function Deployment process (Appendix A). Next, a score from 1 (worse) to 5 (best) was given expressing how well an idea satisfied each specification. For example, the engineering specification Power Consumption was given a weight of 24%, and design ideas were evaluated based on how well they could meet this goal of operating on 500µW. Evaluation scores were assigned based on knowledge gained from background research knowledge and personal experience, as appropriate.

Following evaluation of the seven design ideas against the eight engineering specifications, individual scores were summed to determine a Total Satisfaction rating and then adjusted to reveal the Weighted Satisfaction rating on a 1 to 5 scale. Our system level decision matrix and its results can be seen in Table 8 below.

Table 8. Weighted Decision Matrix for System Level Design Ideas.

	S	M	PO	FS	C	SD	LS	PC	Total Satisfaction	Weighted Satisfaction
Weight	8%	14%	24%	20%	9%	8%	7%	10%	-	-
Stingray with EAP Fins	3	4	3	3	2	2	4	4	25	3.14
Current-driven ROV	1	2	5	3	4	4	2	4	25	3.38
Flounder Fin ROV	2	3	2	3	2	3	4	3	22	2.66
Propeller Submarine	4	4	1	3	3	4	3	2	24	2.72
Impeller Open-Center ROV	4	4	1	3	3	4	3	2	24	2.72
One-directional Benthic Rover	1	1	5	3	4	4	4	2	24	3.18
Stingray with Nitinol Fins	3	4	3	3	4	4	4	4	29	3.48

Key	
S	Speed
M	Mobility
PO	Power Output
FS	Food Source
C	Cost
SD	Structural Durability
LS	Life Span
PC	Power Consistency

For purposes of idea refinement, a score of 3 was chosen as a cutoff threshold. Considering the range of scores earned by our designs (the highest being a 3.48 and the lowest a 2.66), this threshold value of 3 represented the approximate score separating the 50th percentiles, above which designs would be further examined and below which designs would be rejected. The designs earning a Weighted Satisfaction rating of at least a 3 were Stingray with EAP Fins, Current-driven ROV, One-directional Benthic Rover, and Stingray with Nitinol Fins.

6.3 Concept Designs and Risk Management

The results of our decision matrix revealed four system level concepts as strongly favored, earning scores greater than 3 out of a possible total of 5 points. These concepts were one-directional benthic rover, current-driven ROV, stingray with electroactivated polymer fins, and stingray with shape memory alloy fins. Upon further scrutiny, we determined these concepts fell into design alternatives based on levels of risk: low, medium, and high. Risk was determined based on the relative uncertainty surrounding each design's feasibility and complexity.

We viewed the one-directional benthic rover as having the lowest level of risk, using tide/current patterns for one directional locomotion and the MFC's energy output for controlling deployable tide/current sails necessary for harnessing the energy of the ocean around us. This concept's core technical challenges include achieving reliable, one-directional motion and deploying tide/current capturing sails.

The current driven ROV was viewed as the design alternative carrying a medium level of risk. This concept uses microbial fuel cells for more than just their electricity generation potential, capturing the gaseous byproduct CO_2 created by the chemical reaction for use in buoyancy regulation. The design employs buoyancy changes in order to transition from being negatively buoyant and resting on the ocean floor to being positively buoyant and floating in the water column. When hovering in the water column, this design would then deploy tide/current sails (similar to the low risk design) in order to harness the ocean's energy for forward locomotion. This design requires our group can effectively capture and release CO_2 as well as deploy tide/current capturing sails.

Both wing propelled stingray concepts were viewed as high level risk designs, controlled by some type of artificial muscle (either an electroactivated polymer or a shape memory alloy). These design alternatives use buoyancy changes to rise into the water column, but unlike the medium risk design, would have the means to self-generate forward locomotion. An on-board locomotion capability would remove our design's dependency on favorable ocean tide/current conditions and could pave the way for more widespread adoption of our gastrobot's design for underwater exploration. Challenges for this design include providing sufficient power for artificial muscle actuation as well successfully using gaseous byproducts for buoyancy regulation.

6.3.1 Platform

Our team decided to pursue a biomimetic stingray shape as our ROV's platform. The use of biomimicry will also complement the microbial fuel cell, itself enacting digestion performed by most organisms. The stingray is an efficient swimmer with a hydrodynamic frame and an inhabitant of both the sea floor and water column (our zones of operation). The body, or fuselage, will house the bulk of the MFC, storage systems, and electrical components, while the stingray's sides and tail will provide control surfaces for various modes of propulsion and attitude adjustment.

The stingray will move to its various waypoints by transitioning from movement in the water column to resting on the benthic floor. The transition from water column to anchoring on the sea floor was chosen because it resolves many of our design challenges: negates unpredictable terrain along the sea floor, provides a period for the rover to charge to keep up with its exceeding power demands with the MFC energy production, the ability to wait out impeding current flow and move when conditions are ideal, and for future teams to develop a means of 'feeding' on the benthic soil while the stingray is anchored. Buoyancy control, to be discussed in further detail later, will be achieved by the expanding and purging of an air bag using the CO_2 gas naturally produced by the governing chemical reaction of an MFC.

6.3.1.1 Low Risk Design

Our low risk design will be the one directional benthic rover. This will be designed using the stingray platform and will travel on the sea floor on unidirectional tank treads. A sketch of the system can be seen in Figure 29.

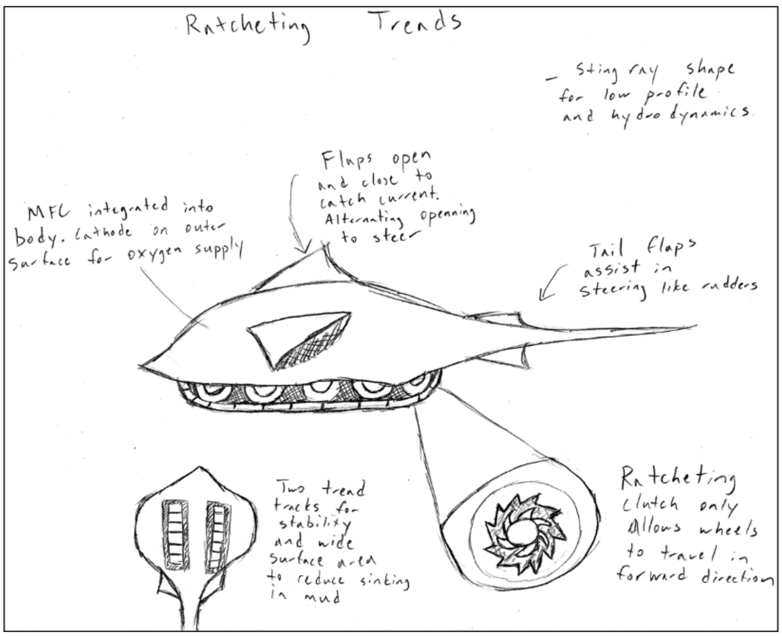

Figure 29. Sketch of the one directional benthic rover.

Its method of propulsion will be actuation flaps on the chassis that will catch currents or tides, similar to a sail in wind. The tank treads will be unidirectional due to a one-way clutch bearing that will only allow rotation of the sprockets in one direction. An example of a one-way clutch bearing we can use is the CSK8 one-way sprag clutch bearing, as seen in Figure 30 below.

Figure 30. CSK8 One-way sprag clutch bearing [40]

The bearing only allows rotation in one direction due to the cage of sprags, which are asymmetrical components that replace traditional cylindrical rollers. The sprags are loaded with a small spring that preloads friction contact to the inner race. Due to the design of the spring system as well as the sprag shape, the sprag will compress and allow the outer race to rotate around the inner race. However, when the rotation is in the opposite direction, either the geometry of the sprag will create a frictional force or the sprag will catch in the geometry of the inner race, locking the rotation of the outer race in relation to the inner race [41]. The engaging and disengaging of this clutch can be seen in Figure 31 below.

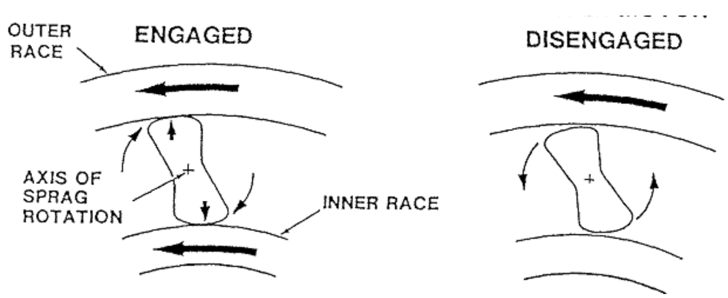

Figure 31. Sprag clutch locking relative rotation (Left), allowing rotation (right) [42].

The main strength of the one directional benthic rover is the simplicity of the system, the main reason we deemed this design the low risk design. The MFC will only be utilized in controlling the actuation of the flaps to catch the currents. The tank treads unidirectional travel is purely mechanical, making the propulsion minimally complex.

The main challenges this design faces are sealing the components of the tank tread system from the ocean, maintaining an upright orientation, and activating the flaps at the right time. The performance of the bearing is highly dependent on preventing corrosion on metal components, as well protecting the sprags from water and mud. There will be considerable design challenges in protecting the bearing from the ocean for this reason. Because our design is intended to only travel in one direction, the low risk design faces the possibility of flipping over if we cannot prevent a cross current from lifting the ROV out of its upright orientation. Our ROV will not be able to travel in the intended direction if it is out of the proper orientation. Finally, this design is highly dependent on being able to activate the flaps at the right time to catch the currents. While it is possible to preload designated times of flap actuation based on tide charts or to install sensors to read currents, they both will add more complexity to our design.

Future design considerations will be concerning the flaps. Time permitting, we may be able to design a system that will control the angle of the flaps or independently actuate the flaps to control of the direction of travel from the push of the current in a method similar to a sail boat. Furthermore, if we can harness the power output of the MFC properly, the actuation of the flaps may provide propulsion similar to the labriform locomotion of penguins or sea lions.

6.3.1.2 Medium Risk Design

Our low risk design has large potential in tapping into available energy but it poses a few limitations: ground resistances when moving and navigating the sea floor. An alternative solution would be to rise into the water column to ride in currents and tidal flows. This would negate any ground resistance, allowing the bot to flow freely through the water. Also, currents are a much more prevailing force in the water column than along the sea floor, providing much larger driving forces for our rover.

For depth actuation to occur we need a method of controlling buoyancy of our stingray so that it may rise into the water column to ride favorable currents/tides and then sink and anchor onto the sea floor to recharge or avoid opposing currents and tides. When in the water column our stingray will ride the current and/or tide with actuated flaps like those identified in the Low Risk Design. Figure 32 below conveys our vision for what an ROV of this type may look like. The blue mesh on each fin represents expandable gas bladders capable of changing the ROV's occupied volume underwater, a requirement for adjusting buoyancy.

Figure 32. ROV Concept Using Buoyancy Changes as a Locomotive Aid.

One of the advantages of operating under water is the illusion of weightlessness and the ability for heavy objects, same mean density as water, to move between various depths with very little apparent effort. We will use a gas bladder system with hands-off pressure release valves, and actuated purge valves to control the buoyancy of our rover so that it may move up and down through the water column.

It is important to realize that buoyancy can be finely tuned, and that the threshold between an objects capacity to sink or float can be altered ever so slightly. A simplified perspective on buoyancy is to compare the weight of an object with the weight of the water that the object displaces when submerged (comparing densities). If the weight of water displaced by the object exceeds the object weight, the object will be positively buoyant and rise. For the opposite, weight of water is less, the object will be negatively buoyant and sink. We can use this phenomenon to our advantage by developing our rover so that it is neutrally buoyant at our operation depth of 6 meters, i.e. the stingray's overall density is the same as the water surrounding it. This can be easily achieved by adding or removing weight; water being already quite dense, will result in us most likely having to add weight. With the craft neutrally buoyant it will only require slight changes in overall density to achieve positive or negative buoyancy, which will induce upwards or downwards movement. We will be taking advantage of the microbial fuel cells CO_2 gas production to control our overall density. The CO_2 byproduct will be used to fill a bladder as mentioned before. The bladder, an inflatable bag, will be fitted with two mechanical valves. One will be a pressure relief valve that will act as a mechanical depth control system. As the gas fills and the bot rises, the pressure in the surrounding water will decrease while the pressure in the bladder will increase from expanding CO_2. The pressure difference will then release gas from the bladder and increase the stingray's overall density and slow ascension or create sinking until the bot has reached a designed depth based off the design pressure of the pressure release valve. This concept takes advantage of waters general incompressibility despite the linear pressure increase with depth. Secondly the bladder will be fitted with a manually activated purge valve. This will be used to force the rover into sinking or to remaining negatively buoyant while anchored to the sea floor. Our team has developed a spreadsheet provided as Appendix E that calculates an estimate for the produced CO_2 from an MFC operating at specified conditions. The spreadsheet uses the governing chemical reactions of the microbial fuel cell, dependent on fuel source, and ideal gas calculations that were proven appropriate using compressibility charts. With a 0.2 W/m^2 (low end of existent MFC technology power production), glucose powered MFC and an electrode surface area of 0.16 m^2 (~16x16 inches), over 60 mL of CO_2 can be produced within an hour. This would be more than suitable to transition our stingray into positive buoyancy if the rover were designed to be slightly negatively buoyant at our operation zones maximum depth. Once again, the stingray's neutral buoyancy can be tailored for a specific depth with the simple addition or subtraction of weight.

6.3.1.3 High Risk Design

The high-risk design will strive to forcedly propel our stingray using its large wings. It will have the same buoyancy control system adopted by the medium risk design. Once in the water column, the rover will have the ability to move willingly through the sea water in stagnant water and slow opposing currents and tides. Preserving the water column/sea floor transitioning with buoyancy control will retain the advantages of allowing the microbial fuel cell bot to descend and charge and to remain anchored when current and tidal movements are too strong to be overcome by our propulsion system. Figure 33 below provides a rendering of what this high-risk design alternative may look like. Notice the red colored EAP material on the perimeter of the ROV, used for simulating the actuation of a stingray's fins and tail.

Figure 33. ROV Concept Showing Electroactivated Polymer Location for Simulated Fin Motion.

6.3.2 Propulsion

It is our team's objective to mimic the movement of a stingray and use the large wings located on the side of the body to propel the rover both forward/back and up/down. The long large strokes will improve locomotion efficiency over a rapid moving high-powered propulsion unit such as a propeller. The movement will be achieved by 'beating' the wings in an upward and downward fashion. The wings themselves will have the ability to tilt along their shared central axis (pitching motion associated with an aircraft) which will change the beating wings' angle of attack, either propelling the craft forward-back and/or up-down. A depiction of the movement can be seen in Figure 34. Notice the rover cannot solely move forward or back but will have to move forward or back with either an increase or decrease in depth per stroke.

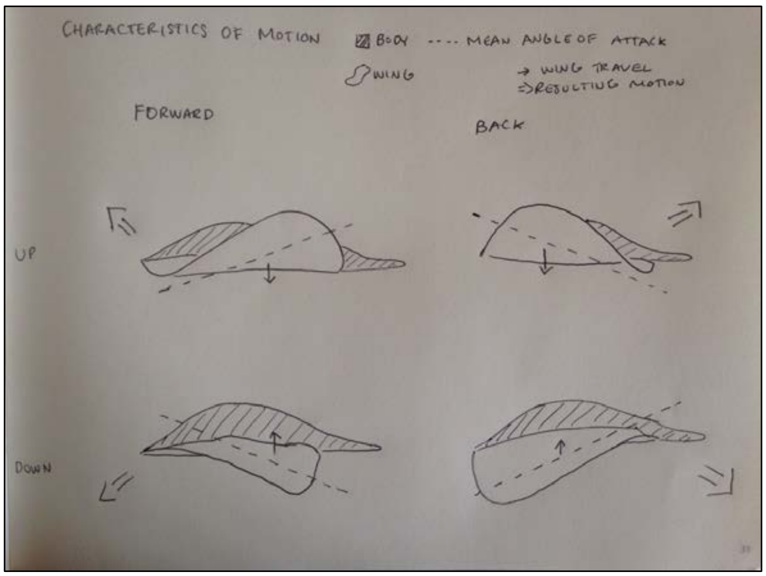

Figure 34. Stingray Rover Motion

Albeit completing our winged propulsion design is highly feasible it may prove to be too large of a challenge. In this scenario, we will adopt an impellor/propeller design to move our rover forward and back. The decision for propulsion actuation will be made prior to the Critical Design Review.

For purposes of setting realistic goals but allowing for design creativity and ambition we have generated two variant means of actuating our stingray's large side wings: Nickel Titanium (Nitinol), and Electroactive Polymers in ascending order of difficulty. In the extreme case that these designs have been deemed too difficult to achieve in our time allotted, we will use a propeller/impellor to provide propulsion as mentioned previously. This decision will be made at the time of the Critical Design Review after more research and testing have been performed.

6.3.2.1 Nitinol

Nitinol (**Ni**ckel **Ti**tanium) is a shape memory metal alloy that exhibits two unique properties: shape memory effect and super elasticity. Nitinol's shape memory ability allows it to undergo deformation at one temperature and then return to its undeformed shape when heated to its "transformation temperature." Nitinol's super elasticity occurs in a narrow temperature range just above its transformation temperature in which the metal exhibits enormous elasticity, 10-30 times of an ordinary metal, permitting it to bend back into its undeformed shape. The shape memory and super-elastic characteristics of Nitinol make it ideal for artificial muscle applications which has made it a suitable candidate for actuating the stingray's wings and tail.

For testing purposes Flexinol®, a nitinol wire brand, will be used due to two primary advantages: published data and low minimum order requirements. Scientific Instruments, the manufacturer of Flexinol®, provides values for wire resistances, pull forces, transition temperatures, and actuation times for the wire. This resource will provide an excellent starting point for research and testing of the use of Nitinol as our stingray muscle actuation. Data from Flexinol® is provided in Table 9.

Table 9. Flexinol® wire properties.

Diameter Size (Inches)	Resistance (Ohms/Inch)	Maximum Pull Force (grams)	Approximate* Current at Room Temperature (mA)	Contraction* Time (seconds)	Off Time 70° C LT Wire** (seconds)	Off Time 90° C HT Wire** (seconds)
0.003	5.0	80	100	1	0.5	0.2
0.004	3.0	150	180	1	0.8	0.4
0.005	1.8	230	250	1	1.6	0.9
0.006	1.3	330	400	1	2.0	1.2
0.008	0.8	590	610	1	3.5	2.2
0.010	0.5	930	1000	1	5.5	3.5
0.012	0.33	1250	1750	1	8.0	6.0
0.015	0.2	2000	2750	1	13.0	10.0

From the data provided by Scientific Instruments, it can be seen that strong forces can be achieved with the Nitinol wire, albeit at high amperage costs. With reasonable time to charge, several minutes, it can be inferred that the rover can perform a few powerful strokes to achieve a forward motion. Mechanical amplification of power through leveraging and pulley systems can also be used to achieve more powerful strokes off reduced power. With the preliminary data, we believe it safe to move forward with testing of Nitinol wire a plausible means of actuation for our stingray rover's wing propulsion system.

6.3.2.2 Electroactive Polymers

Electroactive polymers exhibit size and shape changing characteristics when stimulated by an electric field. There are two main categories of EAPS: Dielectric and Ionic. Electrostatic forces cause dielectric actuation. Dielectric EAPs are capable of very high strains at very low power usage but require large actuation voltages (hundreds to thousands of volts). Ionic EAPs are actuated by the displacement of ions inside a polymer and have the capacity to bend to large displacements and require very small voltages (1-2 Volts). We chose to further investigate Ionic EAPs (shown in Figure 35) due to their low actuation voltage which is more suitable for our low voltage MFC application.

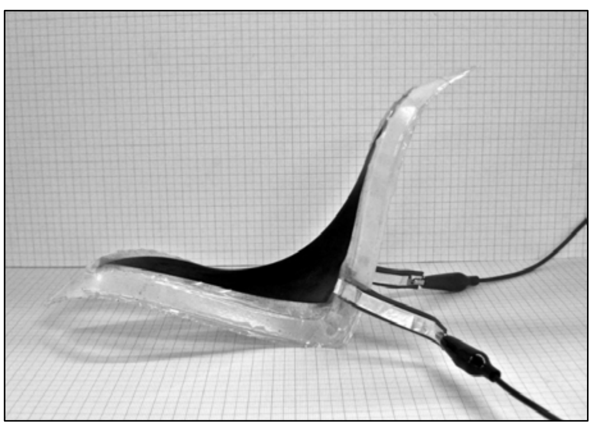

Figure 35. Ionic Electroactive Metal Composite flexing under applied Voltage.

Electroactive polymers come in all forms, including gels. We will use an ionic polymer-metal composite (IPMC). IPMCs are composed of a central ionic polymer like Nafion or Flemion which is then chemically plated or physically coated with conductors such as gold or platinum.

Both Nafion and Flemion are proton exchange materials and have the potential to function in two capacities as both our muscle actuation and MFC proton exchange membrane. The company Environmental Robots Inc. is a distributor of IPMCs and sells material, which we plan to acquire for testing function and feasibility of EAPs.

6.4 Testing

Testing will be performed in a process that complements our design risk criteria. Our priority will be to focus on proving our high and medium risk systems first as they were more highly ranked in our decision process and yield the largest capabilities in terms of underwater rover operation. We began by assessing key functions that will make or break our three designs. For our low risk approach, our team will have to prove the functionality of a one-directional tread system and an actuated flap sail system. Our medium risk shares the sailing requirement with our low risk option as well as requiring we test buoyancy control. Finally, our high-risk concept will require a proof of buoyancy control, like our medium risk, on top of validation of Electroactive Polymers and Shape Memory Alloys as plausible winged propulsion actuators (with our power demands).

6.4.1 One-Directional Motion

This test will implement a one-directional movement system (i.e. treads). We will place the system on a flat surface and ensure that a driving force in its intended direction will incite movement, and that the device locks when forced to move in the opposing direction. A pass will be movement in the intended direction and seized movement in the reverse direction. A fail will occur if the pass criteria is not met. Further testing will require that this be done underwater on a sediment based surface.

6.4.2 Sailing System

The sailing system experiment will test a flap actuation system that can harness the movement of tides and currents to propel our craft. We will place our system on a dummy structure, to imitate mass for momentum and profile for drag, into a water test basin. We will then induce an artificial current to which our rover will passively or actively control flaps or surfaces that will drive it in the direction of the current. A pass will be movement of the rover with the current and maintenance of an operable orientation (as in if the rover is blown into a different orientation by the current it may no longer be capable of functioning properly).

6.4.3 Buoyancy Control

We will begin by pairing our Buoyancy control system with an active microbial fuel cell. The overall system will then be fixated to a structure and weighted so that it is just slightly negatively buoyant at the base of a water tank that we choose for testing. The mock rover will then be left to rise to the design depth, controlled by the tuned pressure release valve. To pass the test the device must remain suspended at the operation depth after transitioning from negative buoyancy at the bottom of our test tank. A secondary test will be performed on our manual purge valve in which case an actuator will be activated to purge the air bag causing the imitation set-up to sink. A pass is given when the device successfully returns to negative buoyancy and returns to the bottom of the tank.

6.4.4 Electroactive Polymers / Shape Memory Alloys

Testing EAP and SMA actuation will require that we propel a dummy mass of our rover design through water at a speed of 0.1 mph, a design specification. The power and voltage requirements of the motion will then be recorded and compared to our MFC power output and rate of energy storage. A pass will consist of a movement speed of 0.1 mph or greater over a small distance and with a power consumption that matches the power output of our MFC or the power generated by an MFC over a period that has been stored via battery or capacitor. This period will be arbitrary but will most likely be no longer than a couple of hours for a few minutes' worth of movement.

6.4.5 Test Process

A snapshot of our test process is located below in Figure 36.

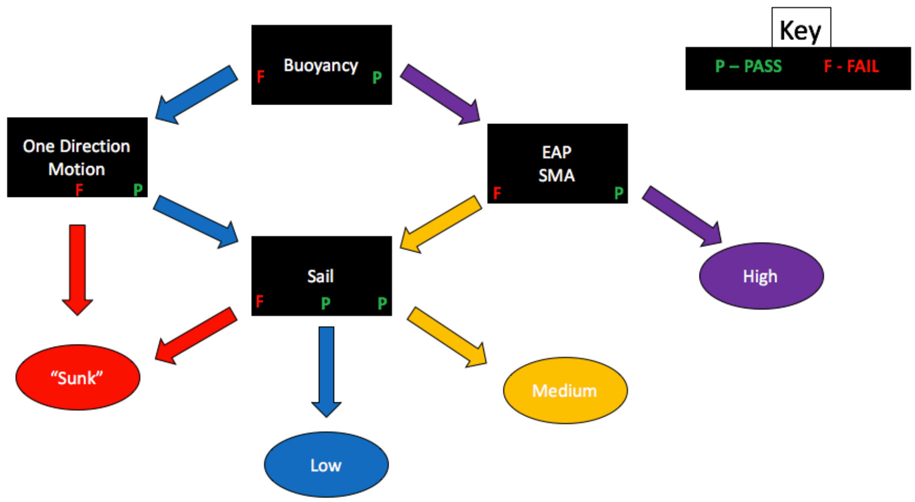

Figure 36: Ocean Locomotion testing process for design risk tiers.

We will begin by testing our Buoyancy Control system as it is a core technology for both our Medium and High-risk designs. There will be four primary projected outcomes during our continued design process.

Scenario 1. If we pass Buoyancy and EAP/SMA testing, we can move along with the design and construction of our high-risk wing propelled stingray design.

Scenario 2. If we pass Buoyancy but fail EAP/SMA testing, we will be required to abandon our high-risk design and look towards our medium risk current rider. With a passing in our sail system testing we will pursue our medium risk alternative.

Scenario 3. If we are to fail our Buoyancy control testing, we will be forced to abandon both our medium and high-risk design goals and test our one-directional motion. If we pass our motion experiment we can test our sailing system, which if successful will put us on track for our low risk design.

Scenario 4. If we fail either our one-directional motion or sailing system, we have failed to prove any of our three design strategies. However, we are confident enough in our designs and their associated risks to not merit any worry for failure.

7 COMPONENT VERIFICATION

After PDR, we tested the components that would define the risk tier our design would be on. These included testing the actuation materials and the gas production of the MFC.

7.1 Gas Production Verification

One of the critical areas of our design risk tier verification was the gas production of the MFC. This condition would dictate if our design could have a level of buoyancy control. However, since this specification is based on technology the microbiology team is making, we were time dependent on the microbiology team making an MFC they were confident on being able to perform gas production capture. However, this team encountered numerous leak issues in their various designs as well as other MFC design setbacks that put gas capture as a later task. After having a discussion with our sponsor Dr. Kitts, we decided to make our ROV neutrally buoyant to a depth practical for design verification. Future development efforts could re-explore gas capture as a means for buoyancy regulation.

7.2 Shape Memory Alloy Verification

One of the actuation materials we tested was the shape memory alloy, Nitinol. For its verification, we placed 18-gauge Nitinol with an activation temperature of 40°C in a test fixture that would run 3.7V at various current values through the wire, heating it to its activation temperature from room temperature (~20°C difference). The test fixture was comprised of the 18-gauge Nitinol wire with alligator clips attached approximately 2 inches apart. A soldering third hand station held the alligator clips. The alligator clips are connected to an HP 6543A DC power supply. The tests were recorded using the FLIR thermal camera that could track the temperature across the wire. The testing set up can be seen in Figure 37 below. In addition, we recorded the time until activation to characterize power demands for meaningful activation times.

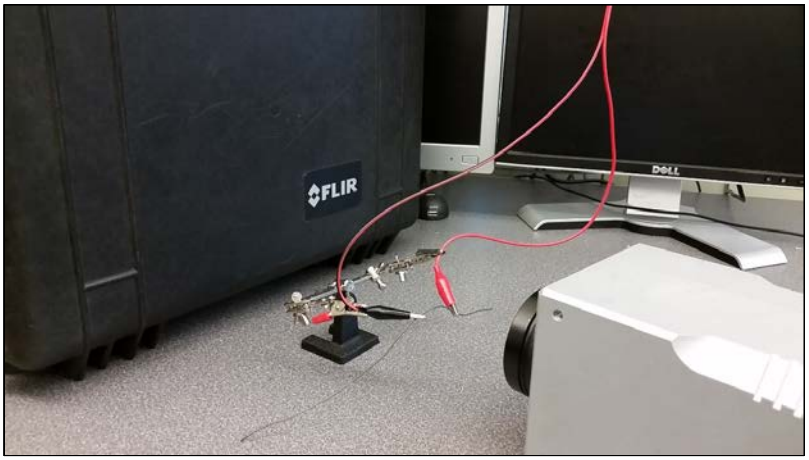

Figure 37. Fixture set up for SMA activation power demands with thermal imaging

The FLIR thermal imaging camera was used to dynamically measure the temperature at various points in the wire while viewing how the heat was being distributed across the wire. This test allowed us to gain an insight to how the SMA would actuate. Figure 38 is a screenshot of the FLIR imaging software, showing the wire at the activation temperature of 40°C. Interpreting data from the thermal imaging, we discovered the SMA would heat from the electrodes towards the center. Although we had anticipated the heating occurring from one electrode towards the other, we found that the heating distribution was even enough to not have detrimental effects of the flap motion.

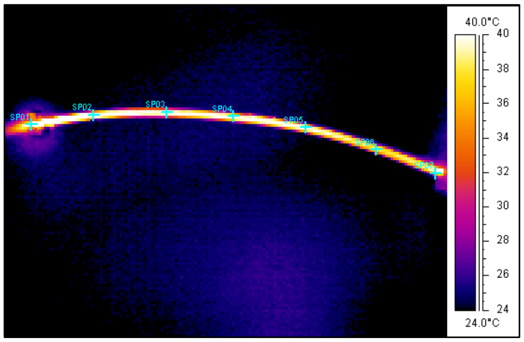

Figure 38. Thermal image of SMA wire at activation. Thermal imaging shows heat distributed from electrodes towards center.

For test data, we recorded the time until the wire reached activation temperature at the various power inputs. The test data is summarized in Table 10. A Time to Activation of Did Not Activate (DNA) refers to the activation temperature beyond 30s. We chose to limit the activation time to less than 30s because we felt that any longer of a period would mean the flap actuates would occur at a rate too low for meaningful propulsion.

Table 10. Results from SMA activation time/power demand verification

Voltage (V)	**Current (A)**	**Time to Activation (s)**
3.7	0.5	DNA
3.7	1.0	DNA
3.7	1.5	14
3.7	2.0	8
3.7	2.5	5
3.7	3.0	5

As seen in our test data, the only practical power demands (3.7V, 1.5A, or 5.55W) occurred at an activation time of 14 seconds, much longer than required for efficient wing flapping motion. Therefore, the SMA proved impractical for the actuation material.

7.3 Electroactivated Polymer Verification

The other actuation material we tested was an electroactivated polymer, Nafion. Nafion is an EAP that will bend with the proper fixture when a current is run through the material. The testing fixture was made of aluminum. Figure 39 shows the testing set up when no power was run through the EAP.

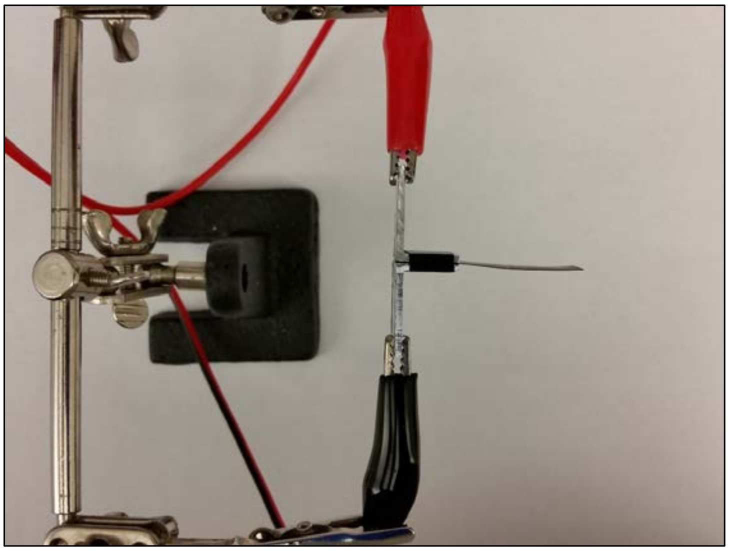

Figure 39: Testing fixture for EAP testing

The testing performed was running a constant current of 0.15A at different voltages. The purpose was to characterize power demands for both activation time and bending strength. Based on documentation on the Nafion, we discovered that the bending strength was dependent on the voltage difference across the Nafion. The Figure 40 below compares the bending of the EAP sample at 3V and 5V.

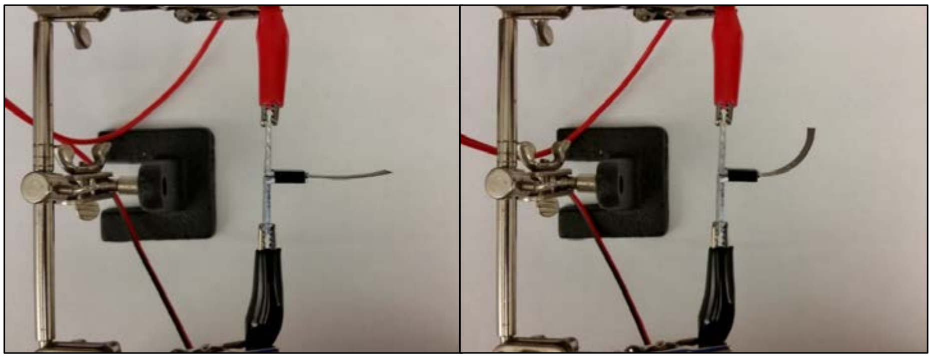

Figure 40. Comparing the bending of Nafion at 3V (left) and 5V (right)

As seen in Figure 40, at lower voltages such as 3V the Nafion only bent a small amount. It was only at higher voltages did the Nafion bend a significant amount. It was during this testing that Nafion was deemed too power consuming relative to the force generated to provide useful actuation. In addition, it is likely a larger size of Nafion would require a larger voltage to achieve the bending necessary. For these reasons, using EAP as an actuation material was deemed impossible.

7.4 Design Decisions

As both of our actuation materials failed, we had to plan on what design we should implement. While the risk tier flowchart dictated that the design become the current catching flap, a meeting between ocean locomotion and our sponsor found that the design would be impractical and not a good representation of the capabilities of MFC technology. This change put us on the path to powering a DC motor for propulsion. While the propeller design would be the most straightforward and simple propulsion method with the motor, we decided to continue with the stingray mimicry and design a mechanism to turn the DC motor rotation to wing wave propagation.

The stingray shape and motion was chosen for several reasons. Many stingrays are benthic creatures and their flat bodies permit them to navigate close to the seafloor. This feature would be useful for a research platform that requires seafloor access to replenish MFC food supplies. The flat body shape also presents significant surface area upon which numerous microbial fuel cells could be mounted. Another reason for this choice is that wing flap locomotion as produced by the stingray is silent and presents nearly zero risk of entanglement with the surrounding environment or its creatures. Conversely, propellers generate significant noise underwater and present a hazard to curious sea life. Lastly, stingrays are also some of the most efficient swimmers, capable of moving great distances (multiple body lengths) with each stroke. If our group can match even a portion of the stingray's efficiency, we will satisfy our project's goal.

Our new locomotion design took inspiration from the Sepios ROV re-creation of cuttlefish locomotion. Both cuttlefish and stingrays exhibit paired fin undulation (as discussed in the background section) with the primary difference being that the stingray uses its entire body for undulation while the cuttlefish has a pair of lateral fins which create this motion. The following Figure 41 below shows the various ideas brainstormed to mimic this undulating motion for the gastrobot.

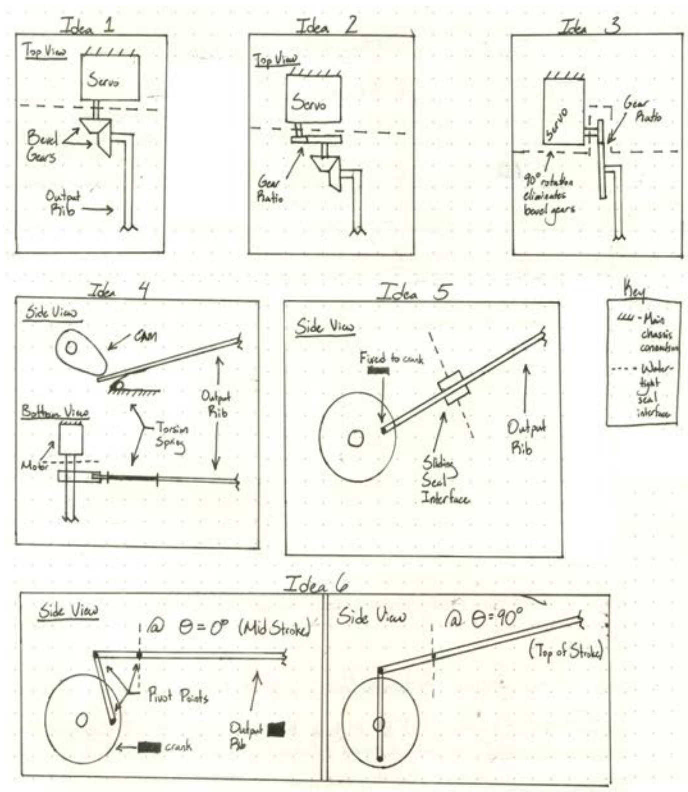

Figure 41. Brainstormed Ideas for Undulating Locomotion.

The mechanisms shown above were each meant to re-create the desired undulatory motion. Idea 6, a crank-rocker mechanism, was chosen as the best of these designs due to its continuous motion characteristic (i.e. no need for microcontrollers to control timing), limited resistance forces, and ease of scalability.

8 FINAL DESIGN

The overall design is comprised of six primary components: microbial fuel cells, energy harvesting electronics, motor and housing, transmission, wings, and chassis (Figure 42). The MFC stingray will utilize MFC energy to drive a crankshaft actuated wing flap propulsion system to allow for fluid motion through our ocean environment.

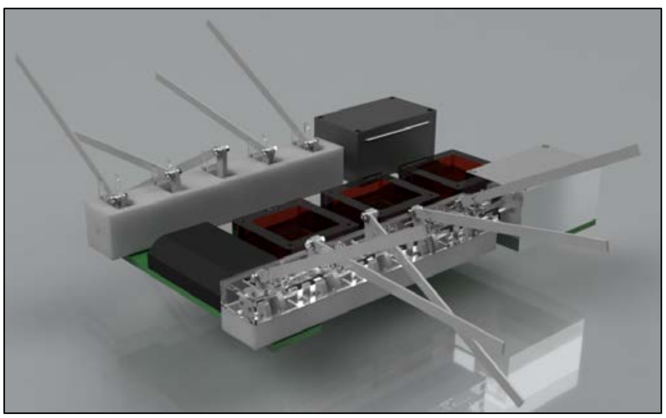

Figure 42. Overall Design of Marine Gastrobot (Latex Wings Not Shown).

The EAP and SAM test results ruled out the practicality of artificial muscles due to their high inefficiencies in comparison to conventional power methods such as DC motors. However, we did not want to abandon our cuttlefish sinusoidal fin locomotion. The fin locomotion provides a robust means of propulsion, cannot be entangled with marine hazards as a propeller might, and mimics one of nature's most efficient swimmers in the stingray. Consequently, we decided to continue with our sinusoidal flap through servo or DC motor actuation. Initially our team investigated the possibility of developing a microcontroller governed flap system in which individual servos would control individual rocker arms to form a sinusoidal wave flapping action. However, due to the small MFC power outputs has led us to diverging from a microcontroller and designing a more rudimentary system. The decision does not exclude the possibility of using a microcontroller but was made to focus our limited time on proving such a system that could be propelled by an MFC. Two motors will power their respective crankshaft transmissions that move rockers that are set out of phase to generate our desired wave flap pattern. The design, although restricted by its inability to have customized flap control, will be an excellent first step in the development of MFC powered robotics by proving that a system can indeed be powered to move from microbe energy. The transmission assembly can be seen in Figure 43 below.

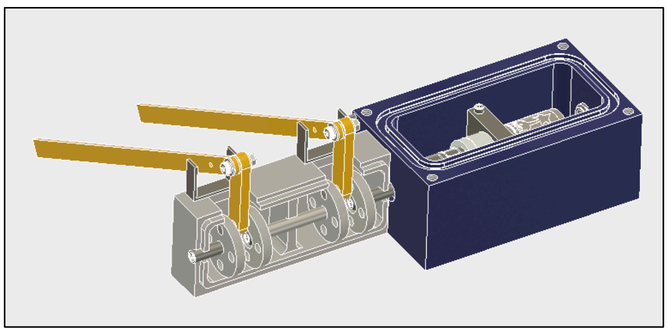

Figure 43. Updated Two Stroke Design of Marine Gastrobot Transmission.

8.1 Overall Design

The overall design is comprised of six primary components described in further detail below: microbial fuel cells, energy harvesting electronics, motor and housing, transmission, wings, and chassis.

The chassis serves as the ROV's structure to which all components are fixed. The final microbial fuel cell design will have an open cathode that will allow for oxygen refreshment for the reactions on the cathode side of the cell. The MFCs will be bolted along the chassis' central axis with the open cathodes exposed along the stingrays back for maximum surface area and water flow. The MFCs will be connected in parallel to boost input current into our electronic energy harvesting circuitry. The energy harvesting unit, safely contained within a water proof housing, will be driven by the TI BQ2555 energy harvester, a DC-DC boost converter capable of charging and discharging batteries or capacitors to pre-determined levels (up to 5.5V). These energy storage elements are then used to power the MFC Rover's two Pololu DC motors and their respective drivetrains. The motors are paired with a gear reduction transmission to provide increased torque and reduced output speed. Each motor has its own transmission system incorporating a crankshaft assembly with rockers that move 90° out of phase from each other, providing a simulated sinusoidal flapping motion similar to that of a stingray or cuttlefish.

8.1.1 Microbial Fuel Cells

The microbial fuel cells will be made from acrylic panels that bolt together to form cavities and walls for anode/cathode chambers and containment, as depicted in Figure 44.

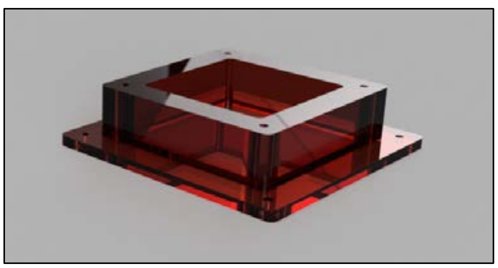

Figure 44. Open Cathode Microbial Fuel Cell

This microbial fuel cell, developed by microbiologists from the Cal Poly Center for Applications in Biotechnology, will consist of an enclosed anode chamber with an open cathode chamber separated by Nafion, a proton exchange membrane. Due to limited time and complexity, a sealed anode was chosen rather than designing an anode equipped with a feeding system. If one were to design a feeding system, things to account for would include a food acquisition system (locating and hunting/harvesting), a possible food processing system (simulated digestion for easier metabolic reaction by biofilm), food storage, and feeding (pumped into MFC anode chamber) before being expelled into the environment or storing the waste in a storage container. Our MFC's sealed anode will instead provide energy for a limited time before having to be refueled. This decision was made to allow the development team to focus on the primary objective: propelling a vehicle underwater.

During development of the cathode, it became apparent that ample oxygen was required for optimal performance. Being in an ocean environment with plenty of dissolved oxygen, we chose to adopt an open cathode design. This design choice eliminates the need for an oxygen retrieval or storage system but does rule out the option for series connection of cells (the surrounding seawater serves as a common electrolyte, thus shorting any cells put in series). Global research and development efforts to achieve subsea series connections of MFCs has so proven to be unsuccessful, so it was decided that this challenge is best left alone for the purposes of this senior project.

The exposed cathode will be covered with a fine mesh to allow for water flow through the cathode while protecting the Nafion membrane and platinum coated electrode from external contaminants and potential damage from its environment. As of 2/12/17, tests of the microbial fuel cells developed by the microbiology team under the direction Dr. Kitts, and utilizing platinum infused carbon cathodes, were producing an average voltage of 0.5V and an amperage of roughly 0.3 mA. To boost output amperage, we will connect multiple cells in parallel, thus increasing our overall power, avoiding short-circuit conditions of subsea series connections, and maintaining the output voltage of 0.5V. Acrylic was chosen for its non-corrosive nature and ease of manufacturing using a laser cutter. Two-dimensional designs of MFC "plates" can then be quickly cut, stacked, and sealed to one another to form our individual microbial fuel cells. This design also allows for component swapping if larger electrode chambers are required or if different MFC layouts are adopted.

8.1.2 Energy Harvesting Electronics

The TI BQ25505 (shown in Figure 45 below) is specially designed to extract the milli- to microwatts of power produced by various forms of DC energy harvesting devices (such as microbial fuel cells).

Figure 45. TI BQ25505 EVM Board.

MFCs, being high impedance sources with low power density, make the TI energy harvester chip favorable for our application. The BQ25505 can be purchased as a pre-built evaluation module board (EVM board) to test the chip for its ability to store energy in capacitors/batteries and to discharge at selected intervals. While full circuit board design using the BQ25505 chip would have been possible and permitted ultimate control over the boost conversion process, in the interest of time, Ocean Locomotion has elected to use the EVM board as our end-use electronic component instead. The EVM board has been designed in a manner which sufficiently satisfies our need to boost power.

Preliminary tests of the EVM board using a simulated input for the MFCs and a motor as a system load produced favorable results. Refer below to Figure 46 and Figure 47, respectively, for a picture of the test set up and for a screenshot of the oscilloscope readout.

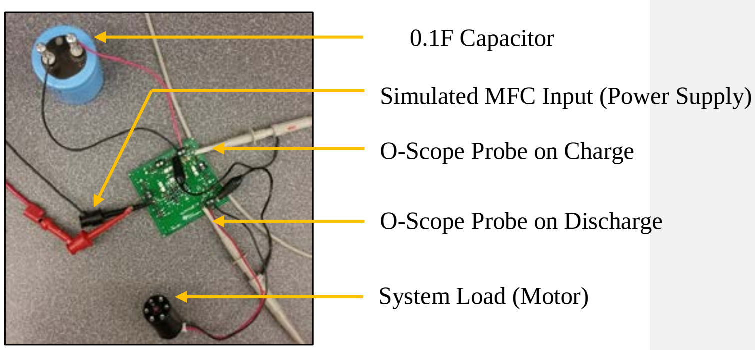

Figure 46. Test Set-Up for EVM Board Testing.

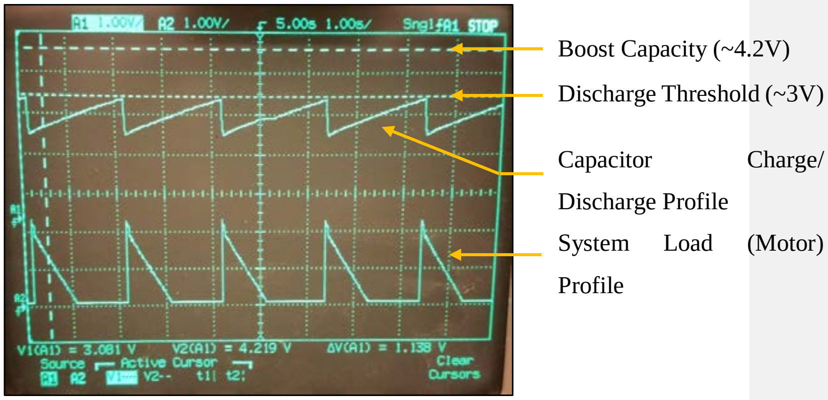

Figure 47. Test Results for EVM Board Testing Displayed on Oscilloscope.

The oscilloscope results from this testing indicate that a system load; such as a motor, can be powered by a capacitor charged by a MFC power source and the EVM boost circuitry. These results give us confidence that higher energy output is possible and, perhaps most importantly, changes the nature of this senior project challenge from one of power dependency to one of time dependency. The boost converter circuitry allows us to take a range of normally unacceptably low power levels and manipulate them to be stored at a higher voltage for later use. MFC power output now becomes a time-based challenge, whereby more energy dense cells will enable a marine gastrobot that takes less time to charge between locomotive cycles.

It is worth noting that this boost converter is not without limits however. This circuitry can produce a maximum output voltage of 5.5V, requires a minimum of 120mV to operate, and needs 330mV to turn on. Current development of the microbial fuel is at or above these threshold levels, and considerations have been made to not require greater than the maximum output voltage.

8.1.3 Housing and Motor

The motor housings' primary functions are to securely mount the motor, align the drive shaft to the transmission shaft, and form a water tight seal to protect all water sensitive parts. The primary components of this subassembly are: housing, O-ring, wiring tap, motor mount, shaft coupler, and shaft seal, and motor.

8.1.3.1 Housing

The housing will be made of machinable 6061 aluminum with a face seal O-ring design as illustrated in Figure 48. The sealing cap will allow for easy access to the motor hardware and transmission alignment and installation. The top access and rectangular structure will allow for ease of handling when fine tuning the assembly.

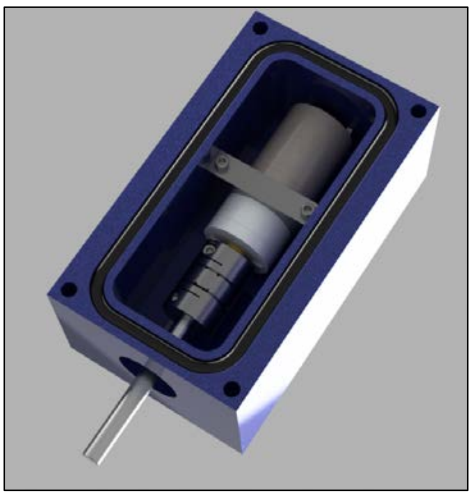

Figure 48. Motor Housing

8.1.3.1.1 O-Ring

An O-ring face seal design was chosen for its superiority relative to a gasket for water-tight seals applications, especially under pressure. An O-ring provides a seal over a much smaller surface area, thus allowing the rings polymer material to diffuse into the macrostructure of the metals surface and sealing off all pathways that could be taken by water molecules. A gasket, although sometimes effective, dissipates the clamp force of the cap over a large surface area and consequently does not achieve the same tight seal. The O-ring face seal was designed per the Parker O-ring handbook.

8.1.3.1.2 Motor Mount

Within the housing is a custom-built motor mount comprised of two separate pieces, as seen in Figure 49.

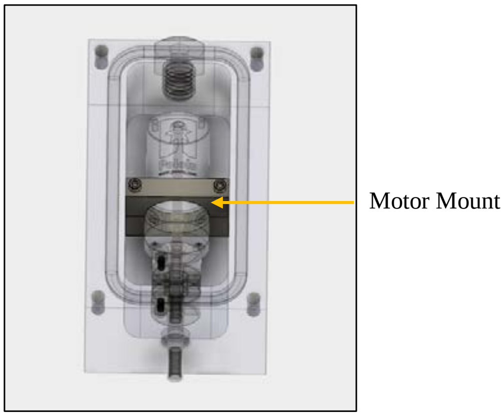

Figure 49. Motor Mount Designed to Fix the Motor to the Motor Housing.

The bottom piece's exterior mounts directly to the flooring of the motor housing's primary case using two #4-40 stainless steel bolts. The top motor mount then vices the motor in place using an additional two #4-40 stainless steel bolts. The mounting method allows for axial movement of the motor providing room for installment and adjustment for possible part changes, such as different motor or shaft coupler sizes. Developing our own motor mounts and making the motor housing modular allows for the possibility of using different motors as the ROV is further developed. The mounts themselves are easy to machine, requiring very few operations. The mounts' inner radius is sized for the chosen motor.

8.1.3.1.3 Shaft Coupler

The motor is then paired to the input transmission shaft, which enters the motor case through a shaft seal using a standard hub and spider shaft coupler (Figure 50) capable of up to 0.011" and 0.8° of misalignment.

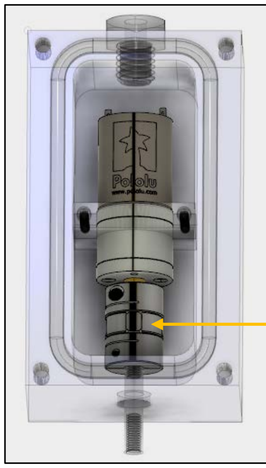

Figure 50. Shaft Coupler for Diameter Transition from Motor Output Shaft to Drive Shaft.

8.1.3.1.4 Shaft Seal

The shaft seal is made of heavy duty graphite-enforced PTFE with a stainless-steel retaining spring. The seal was chosen for its excellent wear and corrosion resistance.

8.1.3.2 Motor

Motors were selected based on desired frequency of wing flapping, speed of flap actuation, and torque requirements where torque was calculated as a force at a distance required to overcome the inertia of the surrounding water. Motor torque requirements from the wing actuation are described in further detail under the Wing Design section.

8.1.4 Transmission

The transmission consists of five crank-rocker mechanisms, each subsequent one 90° out of phase from the last, permitting a full sine wave to be generated and seen at any point in the shaft's rotation. Kinematic analysis was performed to design this mechanism as a four-bar linkage. More specifically, since this mechanism is a crank-rocker, its Grashof condition satisfies $l + s < p + q$ where l is the length of the longest link, s is the length of the shortest link, and p and q are the lengths of the remaining links. Crank-rocker mechanisms are characterized by their continuously rotating input (crank) and their limited range of motion output (rocker).

Design of this mechanism was done in such a way that the top of the stroke where the velocity of the rocker approaches zero corresponds to the least torque being transferred from the drive shaft. Similarly, the middle of the stroke through which the rocker passes the sine wave's zero point and the rocker has the fastest velocity corresponds to the greatest possible torque being transferred from the drive shaft. Refer to Figure 51 below to see the analysis performed for this subsystem.

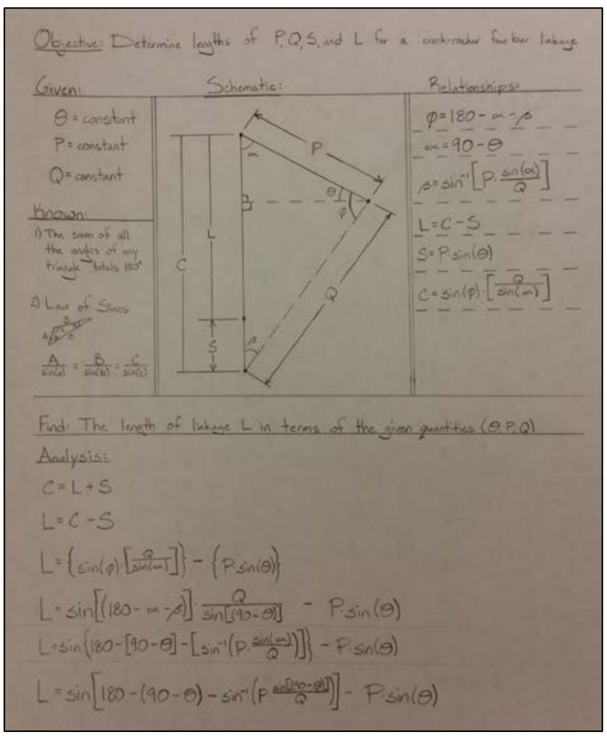

Figure 51. Analysis for Determining Required Linkage Lengths for Crank-Rocker Mechanism.

Values for rocker length and sine wave amplitude were determined per studies done on sinusoidal locomotion that revealed maximum length and a maximum amplitude of 45° were optimal.

8.1.5 Fins

The fins will be comprised of latex sheets connected to the transmission's rocker arms. Latex was chosen from a research design project Sepios in which a team from ETH Zurich in Switzerland built an underwater robot with sinusoidal actuating fins. Their extensive research pointed to latex as the wing material of choice due to its low water permeability and relatively high flexibility. These wings will be made of a rectangular latex sheet that lays over the two rocker arms, wraps around each, and is then adhered to itself forming a sleeve for the rocker arms to fit through. The latex will be attached when the two rockers are farthest apart from each other (one at a local minimum, the other crossing zero) with some slack permitted at this farthest stroke and more developing as the rocker arms change position.

This method of attachment will minimize any forces torqueing the rockers inward, while providing a slightly inflated control surface at all times, much like a paraglider's wing, to better develop forward thrust.

Wing thrust analysis was performed by first using a simple model of a single wing and computing the forward force required to overcome drag during a complete cycle of a single flap. The computation used the drag equation and the drag coefficient of a flat rectangular plate at a specific attack angle to the direction of travel (Figure 52). Results from these calculations allowed us to determine the motor torque required to generate forward thrust capable of moving at our desired speed of 0.1 m/s.

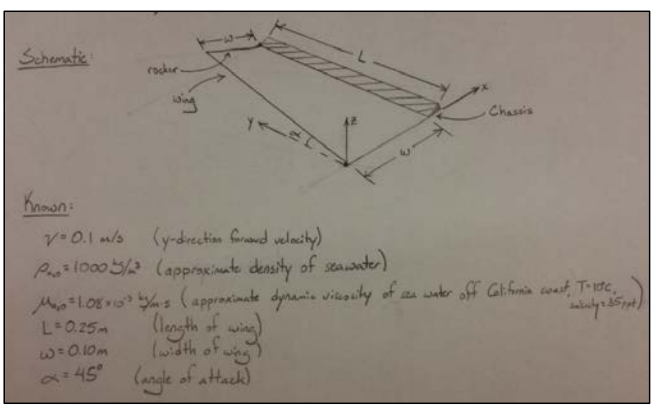

Figure 52. Schematic Showing Approximation of Wing as a Flat Rectangular Plate.

In the interest of determining the torque requirements for a full sinusoidal wave flap, the angle of attack method was integrated along the path of a sinusoidal wave of specific length, tailored to the wing itself, using the derivative of sin(x) = cos(x)*45 degrees (Figure 53). Using the previous calculations, we could estimate the torque requirement of our motor before the transmission losses.

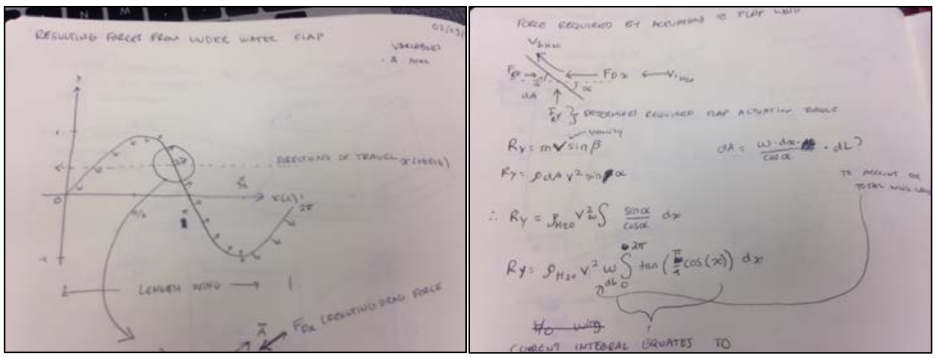

Figure 53. Bernoulli's Iteration across Sinusoidal Wave.

8.1.6 Chassis

The chassis is to be made of a single sheet of acrylic. The chassis itself will be two-dimensional, un-accounting for its thickness of ½", to allow for easy manufacturing and easy bolt-on assembly of the various components. The flat chassis and low-profile components will adopt a suitable shape, wide and long with little height, to accommodate a stingray shaped shell casing. The final design of the chassis and this possible casing are still under development, pending further progress from the microbiologist research group on MFC design.

8.1.7 Stingray Outer Layer

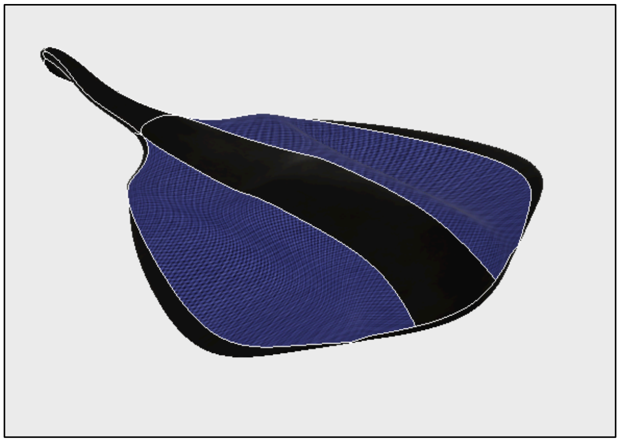

Figure 54. Stingray Outer Casing and Latex Wings

Due to time constraints, a stingray outer layer as seen in Figure 54 above will most likely be exempt from this project. Reasoning for this decision is that the outer layer, despite adding protection and aesthetics, does little to improve our current ROV's performance when "swimming" through the water. A target speed of 0.1 m/s will provide insignificant drag forces on the rover itself, thus negating a need for an outer layer.

8.2 Addendum

Following feedback gathered during our CDR presentation, Ocean Locomotion has elected to pursue a two-stroke crank-rocker assembly. Significant concern was raised over possibilities of shaft misalignment and crank-rocker seizing should our original five stroke assembly be pursued. Heeding this advice, we have decided to reduce our mechanism down to two crank-rockers on each side rather than the original five. While this change no longer permits us to generate a full sine wave profile during locomotion, the two-stroke mechanism will still trace out a sinusoidal profile but in quarter wave increments. Figure 43 above showed an updated model of this two-stroke design.

A plan of attack has been developed to address concerns regarding mechanism functionality (refer to manufacturing plan section). Should the crank-rocker design fail, a propeller will be employed to generate forward thrust. Further details and rationale are provided in the manufacturing plan section.

8.3 Cost Analysis

A full bill of materials (BOM) including the cost breakdown can be seen in Appendix G. With our current design, the overall cost of the prototype is estimated to be $625.28. The most expensive component will be the motor assembly, which includes the housing. Each motor assembly costs $223.73, and we will have two motor assemblies on our final design. As seen in the BOM, most of the components and hardware will be purchased through the McMaster-Carr website. If all current parts are purchased on McMaster-Carr at once, the total bill would be $306.91. The exact part to be purchased can be found by following the McMaster hyperlink for each component on the BOM. The delivery time is expected to be 3-5 business days after the order is processed. To be conservative, we will assume a delivery time of two weeks. Shipping will be free for our order.

The other components are specific components that can be found from separate sources. The TI Evaluation board is to be purchased from Digi-Key Electronics for $52.77 including shipping. The waterproof electronic housing is to be purchased on PolyCase for $10.50. The two DC motors are to be purchased on Pololu for $53.85 including shipping. For all three of these purchases, links to the specific part on their respective websites are found through the supplier hyperlink on the BOM. The only part that will not be ordered online is a 20 in. x 32 in. x .093 in. Acrylic Sheet, to be purchased at the local Home Depot for $16.99 including tax. All other components are to be 3D printed on campus. With our current connections with clubs with access to 3D printers, we do not anticipate outstanding costs for the 3D printing. Vendor information can be found in Appendix C. All specification sheets can be found in Appendix D.

As the manufacturing of the certain components are to be done on-campus, we do not anticipate any outstanding costs for the manufacturing. The same is true for the prototype verification. The tests we will perform will not require expensive equipment. Therefore, with a projected cost of $625.28 for the prototype, the small cost of the basic testing equipment such as string, tape and batteries is negligible when compared to our total budget of $4,300. With such a large remaining budget, we are comfortable with being able to purchase parts for repairs and redesigns if time permits.

9 MANUFACTURING PLAN

Most manufacturing will be completed in Cal Poly's machine shops provided to students who have passed their baseline certifications for manual mills/lathes and CNC machinery. Each team member will be assigned to an array of parts and oversee their manufacturing, thus keeping track of our manufacturing timeline.

9.1 Additive Manufacturing

We will be using a MakerBot Replicator 2 to print all our 3-D printed components. The printer's layer resolution of 0.004" should provide sufficient accuracy for modeling critical components such as shaft bearing mounting sleeves.

9.2 Subtractive Manufacturing

Machining of the motor housing will be done on a CNC mill to ensure a quick and clean bore of the motor chamber. Laser cutting of crank-rocker components will occur on the laser cutters in Mustang '60.

9.3 Project Plan of Attack

The purpose of this plan is to ensure that the development of a functional marine gastrobot locomotion system is successful. Figure 55 and accompanying description detail the steps required to develop our team's preferred locomotive technique (crank-rocker mechanism array) while avoiding overall project failure should the challenge prove too much for our timeline. If development of the preferred locomotive technique fails, a secondary locomotive technique (propeller drive) will be employed. Failure is to be determined by group consensus at any time or by insufficient progress at the time of our go/no-go date for manufacture (3/6/17). Refer to the diagram in Figure 55 below to understand the flow of this plan.

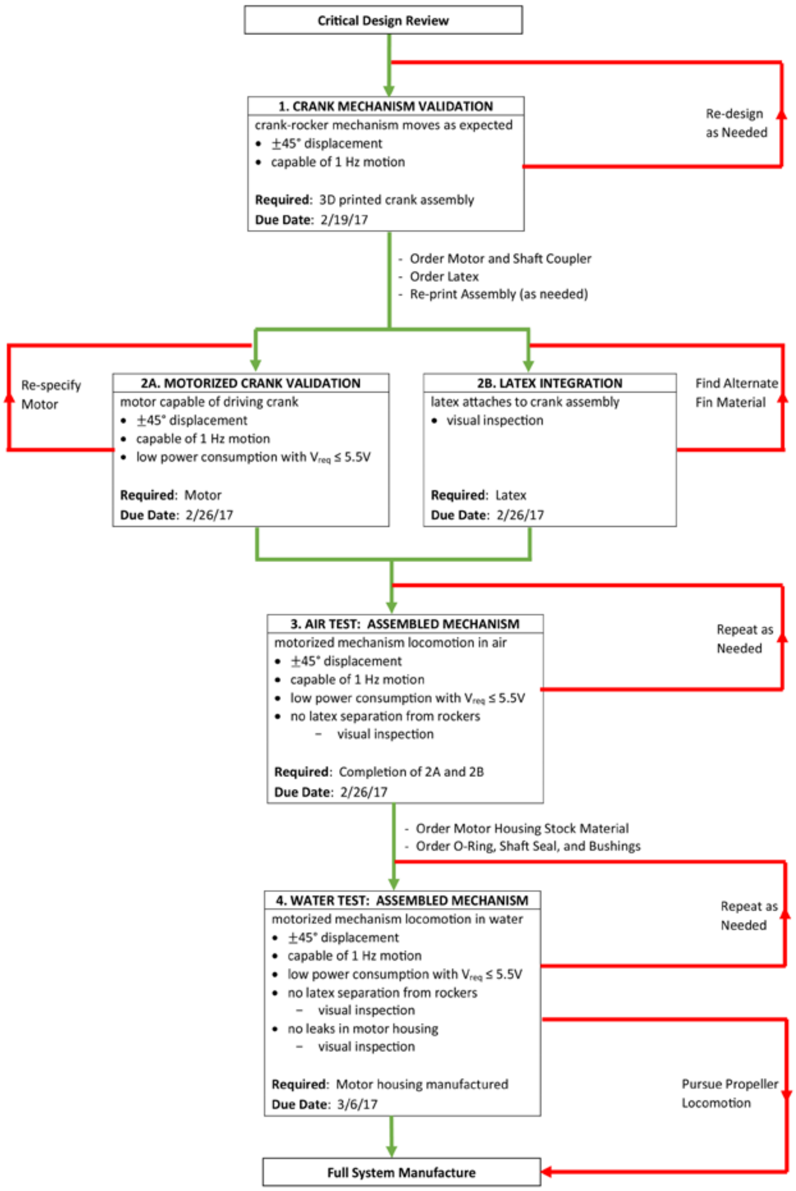

Figure 55. Flowchart of Key Steps in Developing Crank-Rocker Locomotion System.

9.3.1 Crank Mechanism Validation

The first step in developing the preferred locomotion system is validating that the crank-rocker mechanism works as designed. A full-scale locomotion system will be 3D printed and assembled by members of Ocean Locomotion. The mechanism will then be actuated by hand and measurements will be taken to validate that the mechanism achieves a full stroke ($\pm 45°$) and rotates at the desired speed (1 Hz). Should the crank-rocker drive train not function properly (e.g. seizing linkages, misaligned shafts, excessive system friction), iterations on the design will occur until the mechanism works as intended or a consensus has been reached to pursue the secondary locomotive technique.

9.3.2 Motorized Crank Validation/Latex Integration

The second step contains two parts that can occur in parallel. Step 2A is to motorize the crank-rocker assembly, accomplishing the same functionality as required by step 1 while also operating on low power. The low power requirement is somewhat relative, permitting at most 5.5V and current in the micro- to milliamp range. The voltage is capped at 5.5V from the boost converter circuitry (the chip cannot boost the input beyond an output voltage of 5.5V). The maximum current available is a function of MFC size and efficiency; since the fuel cells are still being developed by the microbial fuel cell research group, an input or output current value is hard to determine now. Overall power will likely need to be under 5W for the final design to balance vehicle speed with energy storage device discharge time.

Step 2B is to integrate the latex onto the crank-rocker assembly. The latex will be fixed to each of the rocker arms and sized to not be overly taut to avoid unnecessary side force on the rocker arms. Success for this step will be determined by visually inspecting the assembly to assess the fidelity of the attachment. If the assembly can rotate without significant latex separation, this step will be complete. Otherwise, a different thickness of latex or else a different connection material will be sourced and this step will be repeated.

9.3.3 Air Test: Assembled Mechanism

This step is used to test the fully assembled preferred locomotive technique for function. The motorized system will be run with the latex fins attached and validation criteria from step 2 will be applied. Should the system not complete its full range of motion, not achieve the desired frequency, require significant power, or show signs of latex separation; then the root causes will be identified, changes made, and step 3 repeated. It should be noted that the due date for this step coincides with that of step 2. Since this test does not require lead time for any additional components, it is believed that once step 2 concludes, step 3 can begin without delay.

9.3.4 Water Test: Assembled Mechanism

The final step before full system manufacture will be to perform a water test of the assembled mechanism. Similar to the test in air, this step will be evaluated against the earlier criteria, but will also include a water ingress test. Should our system experience water leakage during operation, the test will be aborted and adjustments made. Step 4 also serves as the go/no-go milestone before full system manufacture. Failure in this step or group consensus beforehand will lead to abandoning the crank-rocker locomotive technique in favor of a propeller-driven system.

Due to the prevalence of propeller-driven systems, it is being assumed that this locomotive technique is relatively straightforward to implement (at least at its most basic level) and that much of the engineering work required to test the primary locomotion technique (e.g. boost converting, motor analysis, water proofing) can be used to operate the secondary locomotion technique. The additional components required would include a propeller, higher speed motor, and a method for attaching the two.

Ocean Locomotion appreciates the challenge of pursuing a non-conventional locomotive technique and is prepared to strive to successfully develop this method of motion. However, we are also prepared to adopt a propeller should our efforts prove unsuccessful. We understand the goal of this project quite well (move forward using only a MFC) and are determined to ultimately accomplish this objective regardless of the path taken.

10 DESIGN VERIFICATION PLAN

After we have finished manufacturing and assembly of our prototype, we will move onto our design verification. Our design verification plan will consist of several tests that will examine the prototype to the specifications we set forth. The details of the testing are listed in the following Design Verification Plan and Report (DVPR).

Table 11. Test plan portion of DVPR

TEST PLAN							
Item No	Specification or Clause Reference	Test Description	Acceptance Criteria	Test Responsibility	Test Stage	SAMPLES TESTED	
						Quantity	Type
1	Distance Traveled per Cycle	Test 1 power discharge of ROV in pool, record video for analysis	1 in ± 0.5	Buck	DV	1	B
2	Speed	Test 1 power discharge of ROV in pool, record video for analysis	> 0.1 mph	Tommy	DV	1	B
3	Cost	Keep project spending within budget	< $4300	Tommy	DV	1	B
4	Leak Proof	Submerge and run ROV through at min 1 power cycle, then inspect critical areas	No water damage	Buck	DV	1	B
5	Actuations per Discharge	Test 1 power discharge of ROV in pool, record video for analysis	4 cycles ± 0.5	Eric	DV	1	B

From the DVPR, it can be seen that there will be two main tests that will test several specifications. The first test will test Specifications 1 (Distance Traveled per Cycle), 2 (Speed) and 5 (Actuations per Discharge). The test will be operating the ROV through one discharge of the capacitor in the test tank containing distance markers while being timed. These tests will be done primarily in the salt water tanks located at the Cal Poly Pier. Each team member will oversee recording data for one of the specifications, such as recording the distance traveled, timing the total actuation time, and the number of wing actuations. From the data taken at this test, the

Specifications can be averaged. In addition, assuming the prototype is not damaged, the test can be repeated to obtain better data. For quick charging, we will use a power supply that will charge the capacitor such as a battery. This test will only require our team to purchase materials to make distance markings, the power supply, and a test tank if we are unable to use the salt water tanks. This test will not take more than 5 minutes per test depending on the total time necessary for the capacitor to charge and discharge. The only time limiting factor to the test will be scheduling a time to use the salt water tanks at the Cal Poly Pier. However, it is likely we will be able to schedule multiple days for testing at the Pier. This test is likely to occur in early May, when we finish the manufacturing and assembly.

The other test will verify the prototype's success with Specification 4 (Leak Proof). This test will be repeatedly running the ROV through repeated capacitor discharges to allow for testing the ROV in comparable conditions that would be expected in normal operation. Again, we will be using the salt water test tank and the power supply to rapidly charge the capacitor. The ROV will likely be weighed down or anchored to the floor of the tank to prevent the ROV from constantly bumping into the test tank walls. This test will be run until a predetermined number of discharges is reached, or until failure. Due to the possibly damaging nature of the test, this test will be performed after the first to allow for as many specifications to be tested as possible. The only additional equipment necessary from this test will be material to anchor the ROV to the test tank floor. Again, this test shouldn't take more than one hour, depending on when failure may occur and the time it takes to dissemble the ROV to check for leaks. Again, this testing will occur on a day in early May once assembly and possible repairs are completed after the first test.

The final Specification 3 (Cost) will be measured throughout the design process. As we continue to order parts and equipment, we will refer to a running cost document that will be compared to our budget of $4300. Before any purchases are made, the budget document will be referred to ensure spending doesn't exceed the budget.

11 MANAGEMENT PLAN

Our design team of three will be spending the next eight months designing, analyzing, constructing, and then testing the ROV. Although we will all contribute to every part of the design process, our team will have a role in certain aspects of team management as well as being a lead in a design process or subsystem. Table 12 below shows each member's leadership role in the areas of team administration, the design process, and in subsystems of interest. A more detailed description of roles follows.

Table 12. Distribution of leadership roles among team members organized by area in design process.

Area of Leadership	Eric	Buck	Tommy
Administration	Communications officer	Secretary	Financial Officer
Design Process (Before Prototyping)	CAD Lead	Manufacturing Lead	Ideation and Initial Product Design Lead
Design Process (During/After Prototyping)	Rapid Prototyping and Part Design Lead	Design Analysis Lead	Testing Lead
Subsystems	Propulsion Lead	MFC Optimization Lead	Communication and Control Lead

In the team administration, there will be roles in areas such as finance, documentation, communication, and reports. Eric will be the communications officer as well as the chief editor. He will be the person who engages primary communication with the sponsor and other outside sources of assistance, as well as the person who checks that our deliverables are formatted correctly. Buck will be the secretary of the team. His responsibilities will be to prepare the necessary documentation before, during and after meetings. Tommy will be the financial officer, maintaining the budget, recording expenditures, and preparing necessary documents for reimbursements.

In addition to taking roles managing the team, each person has a lead role during the design process. Tommy is currently taking the lead in ideation and initial product design, keeping the process as productive and creative as possible. Eric will be CAD lead, maintaining organization of all CAD parts and assemblies, distributing jobs to be modelled, and functioning as the redline lead on shop drawings. After the models are created, Buck will be the analysis lead, directing the team through FEA of the structures as well as any necessary numerical analysis of components and subsystems. Given that Eric was CAD lead, he will transition during prototype construction to the lead in rapid prototyping, ensuring that all part and process files are prepared properly. Buck will take on the manufacturing lead, organizing, and distributing the work done in the machine shop, advising on manufacturability and methods, creating CNC files as well as reserving time on the necessary machines. Finally, Tommy will be the testing lead, organizing the testing methods and managing the data collection, storing, and analysis. While these are lead roles, they are not meant to restrict any team members. The leads will be more for organization, efficiency, and accountability during the process and will not hesitate to seek team input as needed.

To make sure that every team member gets the most out of the project, each team member will also take a lead role in the design of a subsystem, performing further research into the subsystem and putting the design into what he feels is the correct direction. Buck will take on the lead designer role in MFC optimization. As the lead in MFC optimization, he will direct the designs that involve maintain the correct conditions for the MFC to operate at peak efficiency. Eric will take the lead on the propulsion method and related components. In this role, Eric will find the most efficient method of movement that the ROV will perform to maneuver. Tommy will be taking the lead role in the ROV's operation systems. This will include how the ROV will be controlled and how each component and subsystem will be integrated and managed. These lead roles are meant to ensure that each team member gains skill and knowledge in an area of interest. All team members will assist in the design of every subsystem and can voice concerns and approval for the subsystem lead's direction. Furthermore, the subsystems' leads will communicate as necessary to ensure that the subsystems are designed to be used cooperatively, ensuring that they will operate together.

All major milestones and target dates for the year are listed in Table 13 below. A more detailed timeline in the form of a Gantt chart can be found in Appendix F. Due to the size of the Gantt chart and its inherent need to be viewed electronically, the Gantt chart provided acts more as a reference to the flow of tasks to be completed in relation to milestones. These milestones will be the sponsor's set opportunities to voice the opinions over the design direction formally, although there will be much more communication during the design process to check the products progress.

Table 13. Major Milestone Approximate Timeline with Deliverables in Bold.

Date (approximately)	**Milestone/ Deliverable**
By 12/2/16	**Preliminary Design Review (PDR) Meeting**
12/8/16	Official Project Timeline
1/31/17	CAD Model Completed
By 2/16/17	**Critical Design Review Meeting**
4/25/17	Prototype Constructed
5/16/17	Testing Completed
6/2/17	**Design Expo/ Final Design Report & Hardware Handoff**

The Gantt chart is a detailed timeline is created upon the dependencies between tasks. As opposed to a traditional timeline that is created by fixing dates as points to completed work by, the Gantt chart we created by connecting the start of a task to the completion of a task that will allow work to be done for the next task. For example, components cannot be purchased until the budget of components is finalized. These relationships between tasks creates a path that our team will take to complete the project. After the relationships are created, the time line is given detail by an allocation of time to complete the tasks. Furthermore, the tasks will be organized by a summary task that encompasses related tasks, such as Prototype Construction. The Gantt chart helps to organize the tasks and allocate time for tasks to complete the deliverables before a milestone that is fixed in date.

The tasks that need to be completed before moving forward will be the analysis of components and systems that will provide information on which of our designs will be plausible, leading to a final design decision we will develop. This step is essential as creating parallel designs will be time consuming and likely result in failure of the chosen design. After choosing the final design, the outstanding tasks will be the designing of the system and integrated chosen components. The final design and plan for construction will be heavily detailed in the CDR. In addition, we will design around any risks and hazards outlined by The Design Hazard Checklist, seen in Appendix H. The Design Hazard Checklist will outline risks posed by operation of the ROV. After receiving approval to move forward from our sponsor, the next important task will be to order materials and components, construct the ROV and test it to our specifications. Time permitting, this will be the point in which we return to construction and improve our prototype. Once we reach a time closer to the expo, we will compile and analyze the most current results to quantify the success of our design.

12 PROTOTYPE MANUFACTURING

Beginning after CDR, Ocean Locomotion began to manufacture components for the transmission and motor housing for component verification before moving onto the final prototype construction. The primary methods of manufacturing were CNC machining, laser cutting, 3D printing, and hand fabrication.

12.1 3D Printing

The first revisions of our transmission housing were 3-D printed for fast turnaround time and used PLA due to its water resistance over ABS. The initial revisions can be seen in 3-D printing allowed for quick production of complex parts with fast lead times. This advantage allowed for rapid revisions in the early design phases. 3-D printing was originally planned for the final transmission housing deliverable but we decided to machine our final components due to the poor tolerances of the 3-D print which made shaft alignment and press fits unrepeatable.

The Crank discs remained a 3-D printed PLA component because of ease of fabrication and the harder to machine D groove for a D pin insert. Because the crank is somewhat load bearing, another manufacturing method such as CNC lathe is advised for future iterations. Due to our high iteration count, frequently printing new cranks, and the relatively low amount of use cycles, the PLA was an efficient and suitable candidate for preliminary manufacturing. As mentioned previously, below are images of the printing process and our initial transmission housing revisions made of PLA. The process and examples of our iterations can be seen in Figure 56 and Figure 57 respectively.

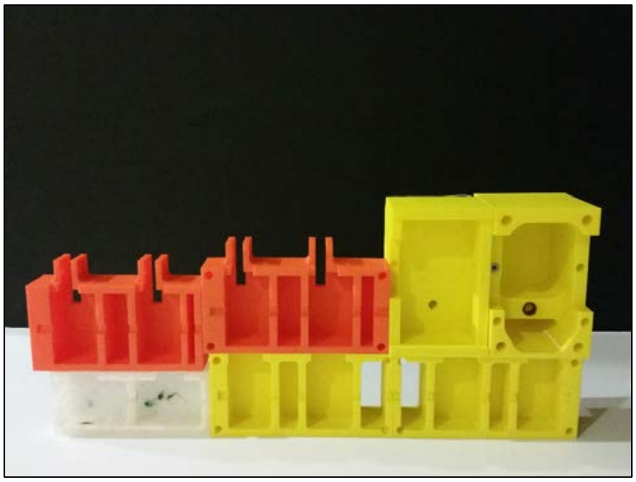

Figure 56. Display of the Seven Transmission Housing Revisions Prototyped with the MakerBot

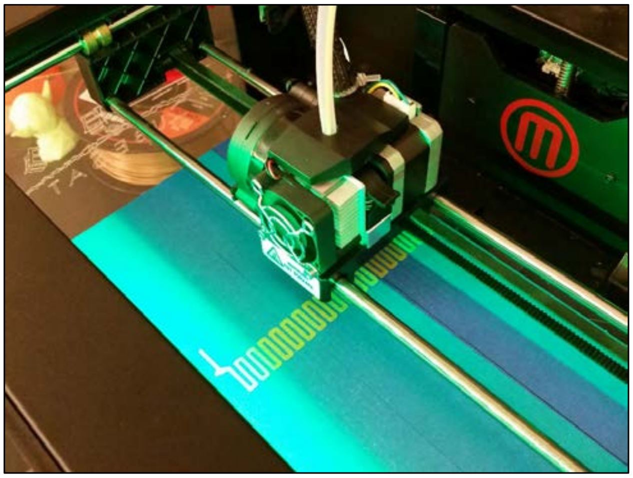

Figure 57. Transmission Housing Prototype Printing on the MakerBot

12.2 CNC Machining

After discovering the need to machine the housing as opposed to 3D- printing them, our team considered the best material to use, including metals and plastics. We chose Delrin based on its easy machinability, anti-corrosion, and rigidity over 3-D printed polymers. A VF3 HAAS Mill was used for the manufacturing of the transmission housings. Air was used in place of coolant to make clean up easier (Delrin chips are flaky and tend to accumulate like ash, see Figure 58). The Delrin held tolerances very well but was difficult to grip in the vice unless the stock was perfectly trued. Double sided adhesive and a large clamping area solved the problem.

Figure 58. Completed Transmission Housings (Left), Residual Delrin Chips, Messy! (Right)

The Motor housing was originally made from Aluminum, Figure 59 and Figure 60. Aluminum is a low corrosive metal when not paired with other metals (forming a galvanic cell) and is easy to machine. However, we decided to switch over to Delrin, Figure 61, to reduce weight and prevent against dissimilar metal corrosion. The motor housing was also manufactured on the VF3 HAAS Mill.

Figure 59. First Motor Housing Revision being CNC Machined on the Haas.

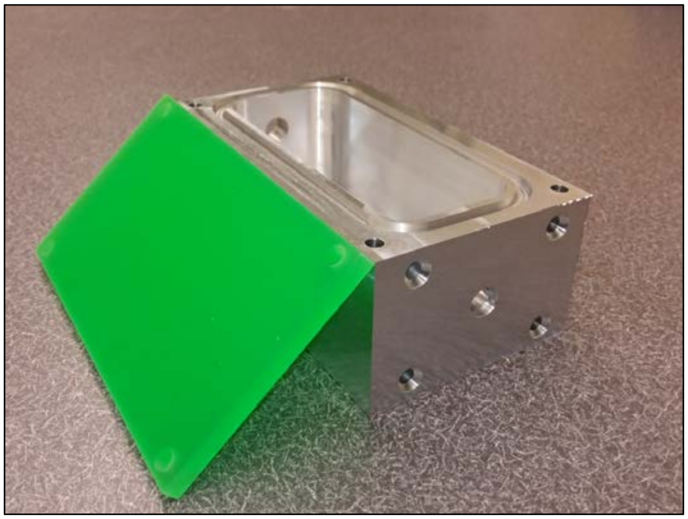

Figure 60. Finished First Revision of CNC Motor Housing with Laser Cut Motor Housing Top.

Figure 61. Second Revision of Motor Housing CNC Machined from Delrin.

12.3 Laser Cutting

A Universal Lasers laser cutter was used for fabrication of the rocker, coupler, motor housing top, and chassis. The material used for the rocker, coupler, and motor housing top were 3/16-inch acrylic and the chassis was cut from 1/4-inch acrylic. Refer to Figure 60 below for a view of the laser system used and to see the motor housing top being cut.

Figure 60. Laser Cutting Motor Housing Top.

Files for laser cutting were generated from the two-dimensional sketches of the parts in CAD. These outlines were exported as a .dxf file type, converted to an Adobe Illustrator file for compatibility with the laser cutting software, and manipulated to vector cut or raster etch for each part. The material used for laser cutting was set in the cutting bed and the z-axis height of the machine was adjusted so that the focal point of the laser was centered in the mid-plane of the material. This adjustment increased the cylindricity of the holes produced using this manufacturing process, permitting improved performance of the final assembly.

12.4 Hand Fabrication

Some portions of the overall design could not be effectively automated using CNC machinery (mill, laser, or printer). For these parts, methods of hand fabrication were used and are described in detail below.

12.4.1 Latex Fin

The fins connecting the rockers were made from 0.35 mm thick latex. The manufacturing of the fins begins by cutting a template from the latex sheet using scissors. The template had the basic shape of a trapezoid with a top base length of 25 cm, bottom base length of 50 cm and a height of 16 cm. In addition to this base layer, three additional strips of latex were cut. From the same latex sheet, we cut 5 cm wide strips that are along the diagonals of the base layer. This allowed the strips to be at the same angle as the sides of the fin. Two strips were cut using this method, one for either edge. Finally, a 5 x 16 cm rectangular strip was cut for the middle rocker.

Attaching the strips to the base layer required a methodical gluing process with patience. The adhesive of choice was rubber cement. A layer of the rubber cement as wide as the applicator brush was applied on the conjoining edges of the strip and base layer. After approximately 2 minutes of drying time, the edges of the strip and fin were aligned. The strip was evenly placed on the base layer, glue side to glue side. The edge was pinched to create a strong attachment and seam. More glue was applied to the latex, across the remainder of the strip and approximately the width of the strip on the base layer. We placed the rocker with the short width on the base layer along this seam, taking care to align the bottom edge to the mark on the rocker. The strip was folded over the rocker and pinched to the opposite side of the strip to the base layer, creating another seam. This process was repeated for the other edge to attach the opposite rocker. Attaching to the middle rocker had a similar process. The only difference was placing the rocker perpendicularly to the midpoint of the bases of the base layer. We allowed the glue to fully cure for 1 hour before further handling. Excess latex was trimmed from above the ends of the rocker, leaving around 1 cm of the fin material above the rockers. This was repeated for the other fin and both had their glue cure overnight before testing.

12.4.2 Preparing the electronics housing

Preparing the electronics housing required the drilling of two holes for the cable glands on opposite sides of the electronics housing. While this can be accomplished with a hand drill, we chose to use a drill press. For our project using a CG-30 cable gland, the recommended clearance hole size is 0.437 inches. We used a 7/16" bit for our project. Using the vise grip on the drill press, the housing was secured and we drilled the holes on both sides. Then the holes were cleaned using a deburr tool to ensure the area around the holes are smooth for optimal seal.

12.4.3 Electronics Preparation

The electronics assembly is comprised of the primary electrical components including the boost convertor, the motors, the capacitor and the MFC, along with the accompanying connections. The manufacturing for this subsystem is preparing various wires and connections. For the motors, short wires are soldered to the leads of the motor. These wires consisted of one red and one black wire to establish polarity convention for the leads for the motors. After soldering, we tested the connection by connecting the motor to a power supply to check if the motor turns on, repeating the soldering as necessary. Heat shrink was applied over the soldered connections, and then the lead and wire were covered with hot glue as strain relief. At the other end of the wire, the male ends of the bullet connectors were soldered on. This was done for both motors, creating a total of four wires with male bullet connectors. Again, heat shrink was applied over the solder for protection.

These were matched with two pairs of the same colored wire pairs, except with one end having the female bullet connectors. The wire lengths were long as necessary to route from the electronics housing to the motor housing. The bullet connectors were connected for the respective wires for each motor. These wires were routed through the black cable gland for the motor housing, and attached the cable gland through the motor housing. Marine epoxy was applied to the cable glands and the hole with the wires sticking through was filled. The opposite four ends of the wires were routed through the grey cable gland for the electronics housing. The outer part of the cable glands was twisted, closing on the wires routed through it. Marine epoxy was again applied to fill the hole and create a seal. The epoxy was cured overnight. The ends of the four wires were stripped and female crimps were applied to the ends of the four wires. The same colored wires were paired and the two crimps were placed through a two-socket connector. This was repeated for the other pair of wires.

Another red and black pair of wires were cut long enough to route from the capacitor leads to the boost convertor, and stripped. At one end of the wires, female crimps were attached to the wire. These crimps were again placed through a two-socket connector.

There are two sets of leads that connect the boost convertor from a power source. The first set connects the boost convertor to a power supply for troubleshooting the propulsion mechanisms. This is a pair of wires that are sheathed in a rubber housing. After stripped away the outer sheath and the wire housing, we soldered the threaded wires to create a better lead for the screw terminals. This wire was routed through the other cable gland and marine epoxy was applied to create a seal. At the other end, a power supply connection was soldered on, and heat shrink was applied.

The second set of leads connect to the MFCs. This will be wires that are of comparable diameter to the leads of the MFCs. These wires were soldered to the wires of the MFCs. Heat shrink and marine epoxy were applied over the connections as necessary to create a seal. These wires were routed through a different grey cable gland and marine epoxy was applied to create a seal.

13 FINAL DESIGN

13.1 Overview

Our completed prototype is depicted in Figure 62.

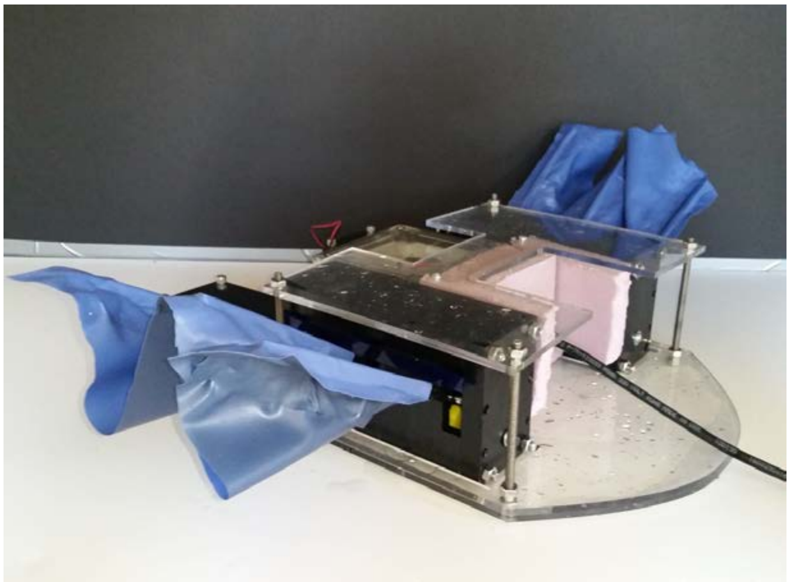

Figure 62. Ocean Locomotion Gastrobot Prototype

As previously outlined, the final prototype has two drive assemblies mirrored about its center plane, with the fins and rockers oriented horizontally for net forward or backwards propulsion. The final designed comprised two motor housings with respective motor mounts, Pololu motors with shaft couplers, and a shaft seal. The electronics housing was placed in the center of the two drivetrains and the entire assembly was sandwiched together with two acrylic alignment plates (one having a stencil of the outline of the rover's various components) and four 1/4-20 threaded rods and nuts. The pink construction foam as seen adhered to the sides of the transmission housings and electronics housing, were used for buoyancy trimming.

A major change in our final design iteration was the transmission housing assembly. Instead of printing or machining two blocks that came together to support and house the transmission components, we decided to design a modular transmission housing, that would allow us to "stack" additional compartment atop one another and allowing us to add or remove the number of rockers in our assembly with ease. The new housing can be seen below in Figure 63.

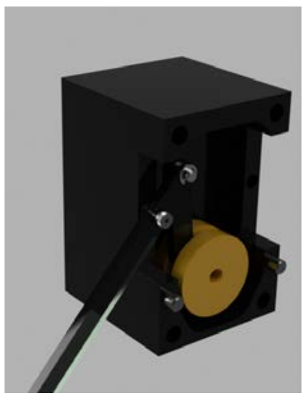

Figure 63. Isometric View of Modular Transmission Housing

Each case has two nominal fit dowel pin hole locations that are used for aligning the transmission cases with one another and maintaining alignment with the primary drive shaft through holes. The transmission cases are then held together with four 1/4-20 threaded rods, two of which screw directly into the mounting face of the motor housings.

14 TESTING

Our testing conformed to our design plan of attack outlined previously in Figure 55. Following the validation of a motor driven flap transmission, we performed three primary tests: floating propulsion, submerged propulsion, and full assembly propulsion.

14.1 Floating Propulsion

Floating propulsion was performed before a fully functional, sealed motor housing was available. The primary goal was to confirm that we generated propulsion with our fin construction. The second goal was to characterize the power consumption of our drive system. As can be seen in Figure 64, a Pololu motor was paired via driveshaft to the 3D printed transmission housing. The set-up had two crank/rocker mechanisms and was placed onto a piece of foam for flotation. The fins were then submerged, the transmission case being rested on its side (90 degrees from the fins intended horizontal orientation) and the Pololu power plant was hooked up directly to a power supply. Various readings were then taken: Voltage, current, stroke frequency, strokes per length of tank, and time to other side of tank. Stroke frequency gave a nice correlation between power consumption and crank speed while strokes per length of tank and time to other side of tank provided a basis for stroke efficiency. It was observed that low stroke frequency enabled the craft to glide between strokes and cover the distance with far less power. Higher strokes up to a certain point proved to be almost as fast if not slower than lower frequencies because of the inefficient thrashing behavior often resulting in turbulent water and sporadic movement. Results can be seen in Table 14.

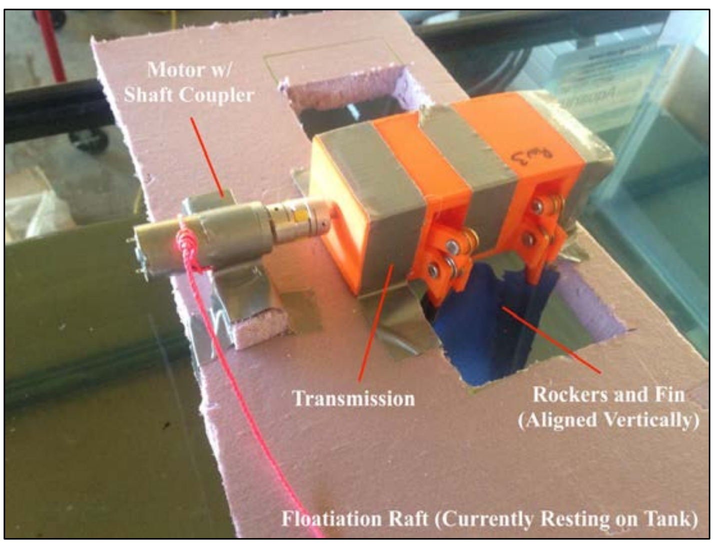

Figure 64. Floating Propulsion Test Assembly

Figure 65. Floating Propulsion Test Assembly (Front View)

14.2 Submerged Propulsion

Our second test involved our sealable motor housing with a shaft seal that deters any water entry from the dynamic shaft movement. Other than the new motor housing and without the floatation foam the remainder of the assembly was the same as our first floating run (two crank/rocker mechanisms housed in our 3-D printed transmission casing). The test objective was to ensure that our system operated without leaks (determined by the dampness of a dry paper towel placed in the motor housing before assembly and testing). We were also once again characterizing the power consumption and stroke frequency. Additional power would then be attributed to the introduced shaft seal and water resistance inside the completely submerged transmission. The submerged test set-up is depicted in Figure 66.

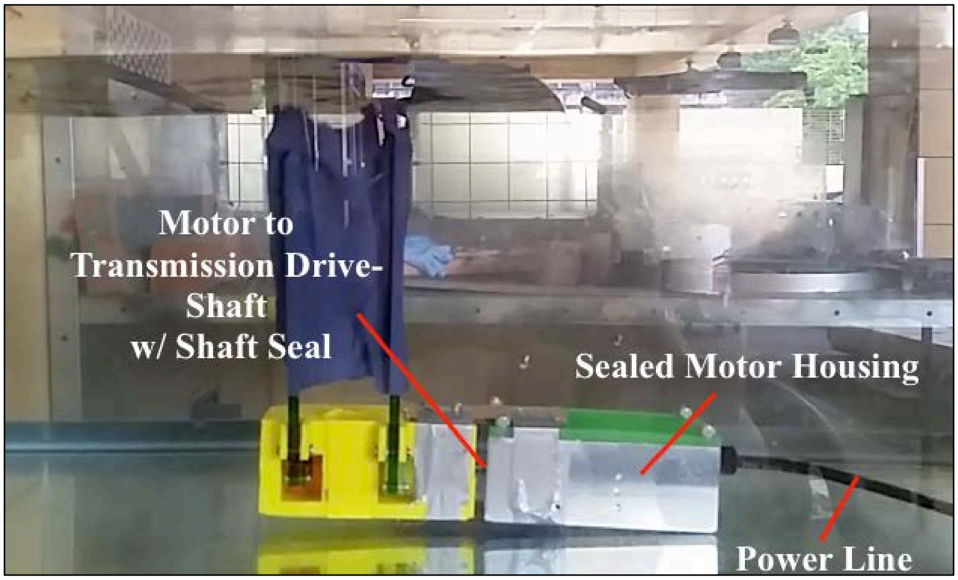

Figure 66. Submerged Propulsion Test Assembly

The entire second assembly was then placed in our test tank. The aluminum motor housing and combined parts proved to be negatively buoyant which consequently anchored the entire power plant and drivetrain assembly to the bottom of the tank. A power supply then once again powered the set-up. Current, voltage, and stroke frequency were all measured. Speed of travel was not recorded because of the anchored system, but despite its weight, the fins were still providing enough thrust to drag the transmission-motor apparatus along the bottom of the tank. Assuming no discrepancies due to anchoring versus free motion (resultant forces from the surrounding water would be roughly the same, ignoring relative speed of water to the craft, whether the vessel was anchored or not) we compared power consumption vs frequencies from our first test to the second test to characterize our power losses and inefficiencies due to the shaft seal and full submersion of our transmission components. Results from our second test (full submersion) and their comparison to the first test are summarized in Table 14.

Table 14. Results and Comparison of Floating Propulsion Test and Full Submersion Test

	Stroke Period (secs/cycle)	Voltage (V)	Max Current /Current Range (A)	Max Power (W)
Float Propulsion	2.8	2	0.2	0.4
Submersion		2	0.08-0.22	0.44
F. P.	2.4	2.5	0.22	0.55
S. P.		2.5	0.08-0.22	0.55
F. P.	1.9	3	0.27	0.81
S. P.		3	0.16-0.6	1.8

It can be observed that power consumption was consistent across tests for higher flap periods. However, as the stroke frequency increased, the fully submersed vessel's power consumption skyrocketed. This was attributed to the increased resistance from the turbulent water, while the floating test would merely push itself to the side rather than bare the entirety of the water's inertia.

14.3 Full Assembly Testing

Due to timeline constraints, we were never able to formally test our overall ROV requirements. However, we did perform a visual test of our prototype's functionality by placing it into our large test tank and watching it propel itself while tethered to a power supply. An image of the testing can be seen in Figure 67.

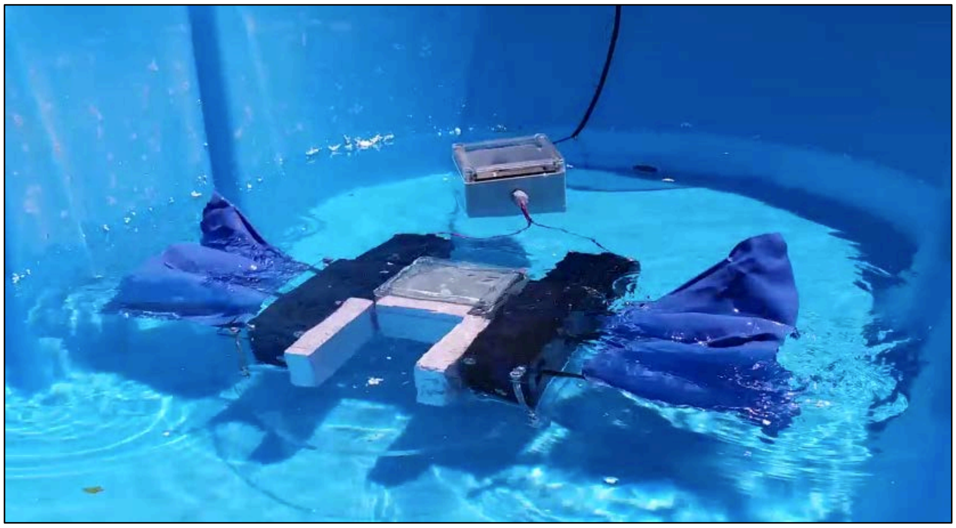

Figure 67. The Gastrobot ROV makes its way through the test tank. A tethered supply line (top of the image) provides power to the rover for testing.

15 CONCLUSIONS AND RECOMMENDATIONS

While Ocean Locomotion succeeded in constructing a working prototype to demonstrate the propulsion method, the project was not able to reach the stage of integrating and testing using MFCs. The complexity of the boost circuitry and issues in arising from inefficiency in the propulsion mechanisms prevented the project's full testing in the time allotted. However, as a first step in a developing product, we are satisfied with the results we have accomplished in designing a marine gastrobot platform to be improved in later iterations.

After completing the construction and testing of the prototype, our team discovered numerous areas in need of improvement. These improvements would lead to a more successful iteration of the ROV. These areas include electrical components, the transmission assembly, seals in housing, weight, and a shell for the exterior of the ROV.

15.1 Electrical Component Recommendations

As a team, we agree a key area of improvement of our project is the boost converter. While we believed that we had a good knowledge of the operation of the boost converter, during the testing of the prototype there were many issues that prevented confidence in integrating the MFCs. For example, there was a cold start condition. This essentially was when a capacitor was not reaching a certain voltage level within a designated period. In this condition, the boost converter reached a time out condition that stopped the charge of the capacitor. This effectively limited the capacitor size we were initially specifying for usage, limiting the period of available discharge time. Another key area we discovered later in prototype development was that the boost converter test board we received limited the threshold voltage limit the storage element could achieve to 4.2V. This could have been changed by altering the resistors on the board, but our team did not have the confidence to change these resistors without damaging the board. Overall, we recommend that this element be given to electrical engineers to analyze and fully understand the capabilities and limitations of the board. From there, they could make recommendations for the viability of using this circuit or find ways to improve the circuit. This is a critical area of improvement because the boost converter makes MFCs as a viable power source for our project.

15.1.1 Motor Recommendations

The motor we chose was a brushed DC motor with a 75:1 gearbox. While this achieved the torque requirements for our design, it is a motor chosen for cost-effective testing should the motor housing seal or transmission assembly fail. However, it is an inefficient motor. A suggestion for a replacement motor was to use a coreless DC motor. A coreless motor has the wires coiled around a hollow cylinder as opposed to the traditional core of iron laminations. These motors have the benefits of lower overall weight, lower rotational inertia, and a lower start voltage of approximately 0.3V. These motors also come with options for gearboxes to improve their torque output. We had initially contacted a representative for Maxon Motors to receive an estimate for a coreless DC motor with a gearbox that would match our specifications. While they did find a promising motor, the lead time and costs made it unviable for our project. This coreless motor would greatly benefit the ROV as the lower starting voltage benefits from the limited discharge output the capacitor would pass from the boost converter.

15.2 Transmission Recommendations

While our transmission assembly worked and performed well, there were numerous areas for improvement as optimization. One area was achieving synchronous movement of the rockers.

15.2.1 Rocker Synchronization Through Crank Disc Redesign

Our design implemented crank discs that were tightened down onto a standoff by a bolt. The offset for the rockers was created manually without a method to achieve equal offset between the rockers on a single fin, let alone between both fins. This led to seizing when the latex was needlessly stretched and improper propulsion as asynchronous fin movement often led to inefficient locomotion. To minimize this, we need to redesign the crank discs. This includes evenly spaced out holes for the pins so only certain angular offsets can be achieved. To ensure the proper alignment between these holes between two discs, a small alignment through hole on both discs should be implemented in a radial location between the center hole and the pin holes. A thin, long pin or rod can be inserted between the holes on the opposite discs, ensuring alignment as the discs are tightened onto the standoffs. This will limit the asynchronous movement between the rockers on a single fin. While this may not improve the synchronous movement between the fins, it will make it easier to calibrate between the two sides as the fins will have closer to identical movements that are out of phase.

15.2.2 Latex Fin

The latex fins are a source for binding. The main issue with the latex was finding the right balance between how taut or loose the latex would be between the rockers. We want the latex to be as tight as possible to move the most water to get more propulsion per stroke. However, too tight and the transmission binds as the motor cannot overcome the tension in the latex. Too loose, however, and the strokes do not move water. Finding this balance was hard, especially when the rockers were more asynchronous than desired. This meant we would have to recut longer pieces of latex and re-glue the seams through trial and error. This trial and error would be reduced once the more modular crank discs are implemented and the angular offset between the rockers can be changed quickly. The fin itself could use redesign. We simply implemented a trapezoidal shape to mimic the shape of fish fins. It is likely that there is a more efficient shape for the fins. This would require consulting a marine biologist for their recommendations. In addition, there could be a more modular design for attaching the fin to the rockers, such as a locking pin closer to the base of the rocker. This would allow for quick changes in the angular offset of the rockers matched by the correct fin length.

15.2.3 Rocker Crank Pin

There is some further improvement in the transmission in the connecting dowel rod that the rocker attaches to. This is currently a round pin in a loose press fit. This allows inefficient motor transmission as the discs can slip out of alignment and decouple. A recommendation is using a keyed joint or a D-cut rotary shaft instead of the dowel rod. This allows for improve torque transmission, preventing the disc slippage. The holes for the rod can de cut deeper to prevent the discs from be decoupled as well.

15.3 Improving Housing Seals

The ROV had critical electrical components that needed to remain dry to operate properly. We developed O-ring seals for the motor housings and bought a commercial waterproof electronics housing, along with cable glands for routing the connecting wires. While performing buoyancy trimming and testing, we found the seals to not performing to the expectations we had.

15.3.1 Motor Housing Seals

The motor housing had surprising leaks. Our initial design with the aluminum and acrylic lid was fairly leak proof so we were confident that the seal would be effective when we changed the material to Delrin and increased the length of the housing. However, we did not account for the bowing of the acrylic lid on the longer housing. This allowed for water to leak through the housing. We found mild success in fixing this by adding an extra layer of acrylic to minimize the deflection in the bottom layer of acrylic. While this worked, there were still some small leaks. We recommend choosing a material less likely to bow under this situation, such as aluminum.

15.3.2 Electronics Housing Seals

As we began testing the prototype, we noticed some failure in the seal of the waterproof housing we purchased. A moderate amount of water did enter the electronics housing as we were trimming the buoyancy of the prototype. Due to time constraints, we could not locate the source of the leaks. Our assumption was the seal around the cable glands. It is possible that there were holes in the epoxy, or the seal around the hole was not optimal. For this reason, we recommend using the marine epoxy more liberally. We recommend adding epoxy to the end of the cable gland leading into the housing, and around the edges of both side of the hole. While this reduces the modularity of the design, it is critical for proper protection of the electronics from water. With time and funding permitting, we do recommend making a custom order for the housing on the PolyCase website. The custom housing options include making the proper holes for the cable glands using CNC, giving a higher guarantee for the seals. We chose to not utilize this option due to cost and lead time for a machining operations we felt confident doing in the machine shop.

15.4 Weight Reduction

Our prototype was surprisingly heavy. While weight does not play a factor underwater due to buoyancy compensation, the mass introduces large inertia that decreases the distance of travel per stroke. The mass can be trimmed from lighter material choices. While a lighter material choice such as polycarbonate would have greater weight reductions, Delrin is far easier to machine and work with. More likely will be using less material. The bulk of the weight came from the motor and transmission housing. The walls could be slightly thinner, and pockets be deeper. There are possible marginal decreases in mass we did not pursue due to longer CNC machining operations.

15.5 Shell Development

Had we had the time, we were going to make a shell to improve the hydrodynamics of the ROV. This shell was going to made from carbon fiber shaped by a Styrofoam mold. The materials were readily accessible from Home Depot, except for the foam. However, with the lead time in preparing the mold and curing the resin, the shell was not made for our final design. We believe the shell would have increased the efficiency of the ROV, improving the distance travel per discharge. In addition, pockets could be made in the shell to act as ballasts for buoyancy trimming. While we do not have a formal design for the shell, it is something we as a team would be beneficial in the next iteration of the project.

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17 APPENDICES

17.1 Appendix A: Attachments for QFD and Ideation

17.2 Appendix B: Drawing Packet

17.3 Appendix C: Vendor Information

17.4 Appendix D: Component Specification Sheets

17.5 Appendix E: Detailed Supporting Analysis

17.6 Appendix F: Gantt Chart

17.7 Appendix G: Operator's Manual

Appendix A. QFD and Ideation

Attachment 1. QFD: House of Quality

Project: Gastrobot, Ocean Locomotion
Revision: #2
Date: 10/20/2016

Correlations	
Positive	+
Negative	−
No Correlation	

Relationships	
Strong	●
Moderate	○
Weak	▽

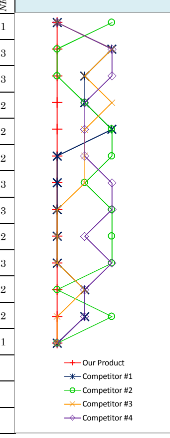
Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

WHO: Customers

Row #	Weight Chart	Relative Weight	Professor Kitts	Microbiologists	Students and Researchers	Ocean Locomotion Team	Cal Poly Pier	Maximum Relationship	WHAT: Customer Requirements (explicit & implicit) \ HOW: Engineering Specifications	Speed	Mobility	Power Output	Food Source	Cost	Structural Durability	Life Span	Power Consistency	9	10	11	12	13	14	15	16
									Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
									Direction of Improvement	▲	▲	▼	◇	▼	▲	▲	◇								
1		4%	1	1	3	3	1	9	Good Mobility	●	●	○		○	○										
2		8%	3	3	3	1	1	9	Low Power MFC	○	○	●	○	●			●								
3		5%	2	1	3	3	1	9	Autonomous Longevity				●			▽	▽								
4		9%	3	3	3	3	2	9	Modularity			●	○	▽	○		▽								
5		7%	3	1	2	2	3	3	Low Environment Impact				○		○		○								
6		6%	1	1	2	2	3	9	Safe	○	○	●	●		▽	▽	▽								
7		5%	2	1	3	3	1	9	Low Maintenance		▽	▽	○	▽	○	●	●								
8		5%	2	1	3	1	1	9	Affordable		●	○	▽	●	●	▽	▽								
9		7%	2	1	3	2	3	9	Easy to Deploy		○	○	●		▽	○	▽								
10		5%	2	1	3	2	1	9	Communication			●		▽	○	○	▽								
11		8%	3	3	3	3	1	9	Easy MFC Interfacing			●	○												
12		8%	3	1	3	3	3	9	Cool Factor	●	●	○	●												
13		3%	1	1	1	3	1	9	Utlizing all Energy Sources		●	●	▽	▽		●									
14		0%																							
15		0%																							
16		0%																							

NOW: Current Product Assessment - Customer Requirements

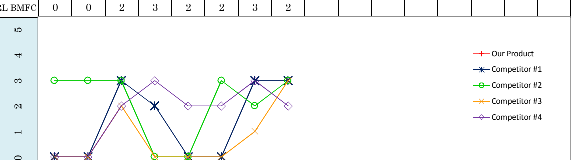
Row #	Our Current Product	MFCs	Open ROV	EcoBot III		NRL BMFC
1	1	1	3	1		1
2	1	3	1	3		3
3	1	2	1	2		3
4	1	2	2	3		2
5	1	3	3	2		2
6	1	1	3	2		2
7	1	1	2	2		3
8	1	1	3	1		3
9	1	1	3	1		2
10	1	1	3	1		3
11	1	2	1	2		2
12	1	2	3	1		2
13	1	1	1	1		1
14						
15						
16						



Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
HOW MUCH: Target	[0.1 mph]	[6in] any direction	[500µW]	Sustain for 1 week	Cost less than budget of $3,000.00	Leak-proof to 30 ft (2 atm), 1 month corrosion resistance	[1 week]	Steady for 1 week								
Max Relationship	9	9	9	9	9	9	9	9								
Technical Importance Rating	148.93	249.97	425.3	346.62	152.72	150	127.1	175.16								
Relative Weight	8%	14%	24%	20%	9%	8%	7%	10%								
Weight Chart																

Current Product Assessment - Engineering Specifications

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Our Product																
MFCs	0	0	3	2	0	0	3	3								
Open ROV	3	3	3	0	0	3	2	3								
EcoBot III	0	0	2	0	0	0	1	3								
NRL BMFC	0	0	2	3	2	2	3	2								



Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

Template Revision: 0.9 Date: 4/23/2010
Christopher Battles

Attachment 2. Two other topics from Overcoming Environmental Challenges ideation

Sediment

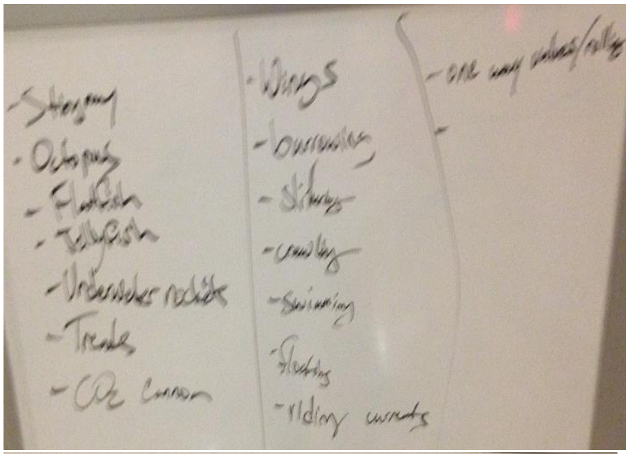
- skiing through soil sand ✓ Sled bottom for gliding
- burying self in sand to recharge
- burying self in sand to separate anode/cathode - Purge cathode w/ CO_2 jets (keep from bury)
- flatfish magic carpet locomotion
- might be advantageous to avoid stirring up dirt clouds
- Slither thru sand like sidewinder
- not much to grip on for pulling
- easy to sink in deep
- sting ray
- wide surface area body to spread out weight & contact
- hop between clam shells
- anchor in sand
- travel bt. sandbars
- dune buggies
- lizard
- snow shoes
- ski poles/cross country skiing
- filter sand for food
- melt sand into glass
- crab scuttle ← king crab, higher elevation
- snow angel

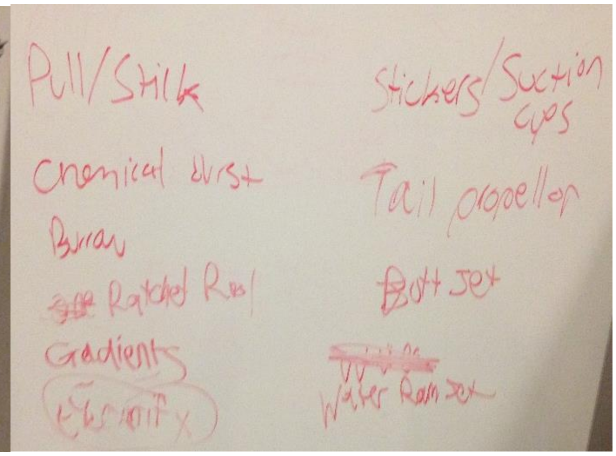
RESISTANCE

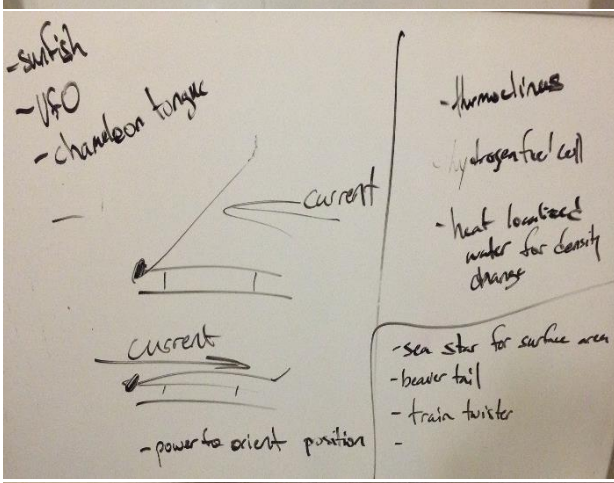
- Water
- Current
- Wall
- Hydrodynamics

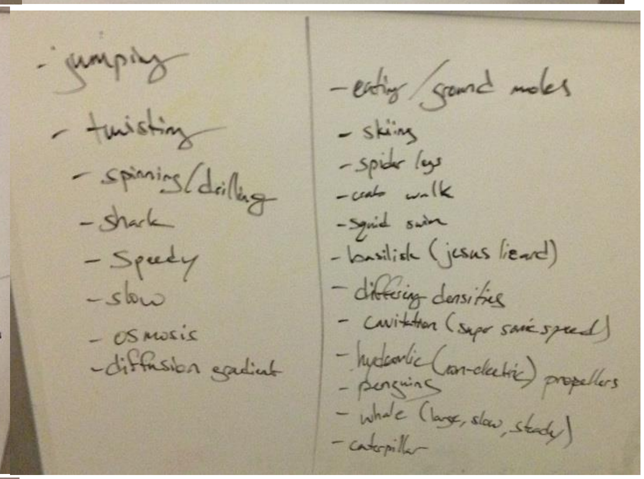
- Loose appendages
- Sleek low to ground profile
- Round cross sections (for easy fluid flow)
- Slimy skin texture
- Attitude control (weight distribution, gyro) to remain in proper least resistance orientation
- Rigid structure
- Openings, for water to pass thru (cage underwater was easy to move.
- Twisting torpedo, like we played w/ when kids
- frisbee spin thru water
- using current charts in look up table to use to advantage
- make it super light and hot air balloon along
- turkey vulture ride thermoclines
- spy plane shape
- use resistance to advantage to anchor & recharge
- use resistance to power another power source (underwater generator to current)
- hop like a frog
- tadpole swimming
- use turbulence to provide steady stream of food (filter?)
- springs
- brittle fracture
- brittle stars

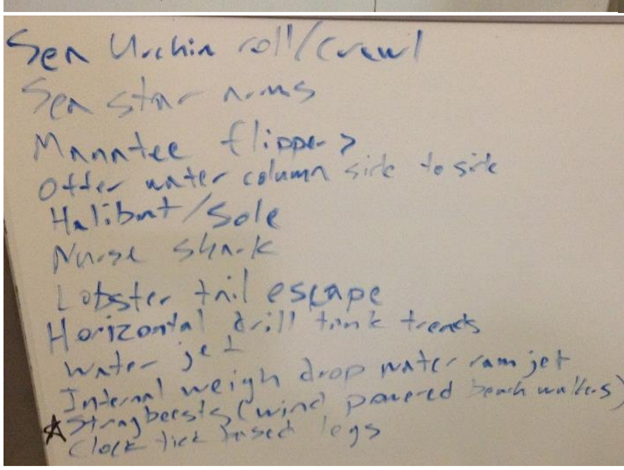
Attachment 3. Photos of ideas from Propulsion ideation



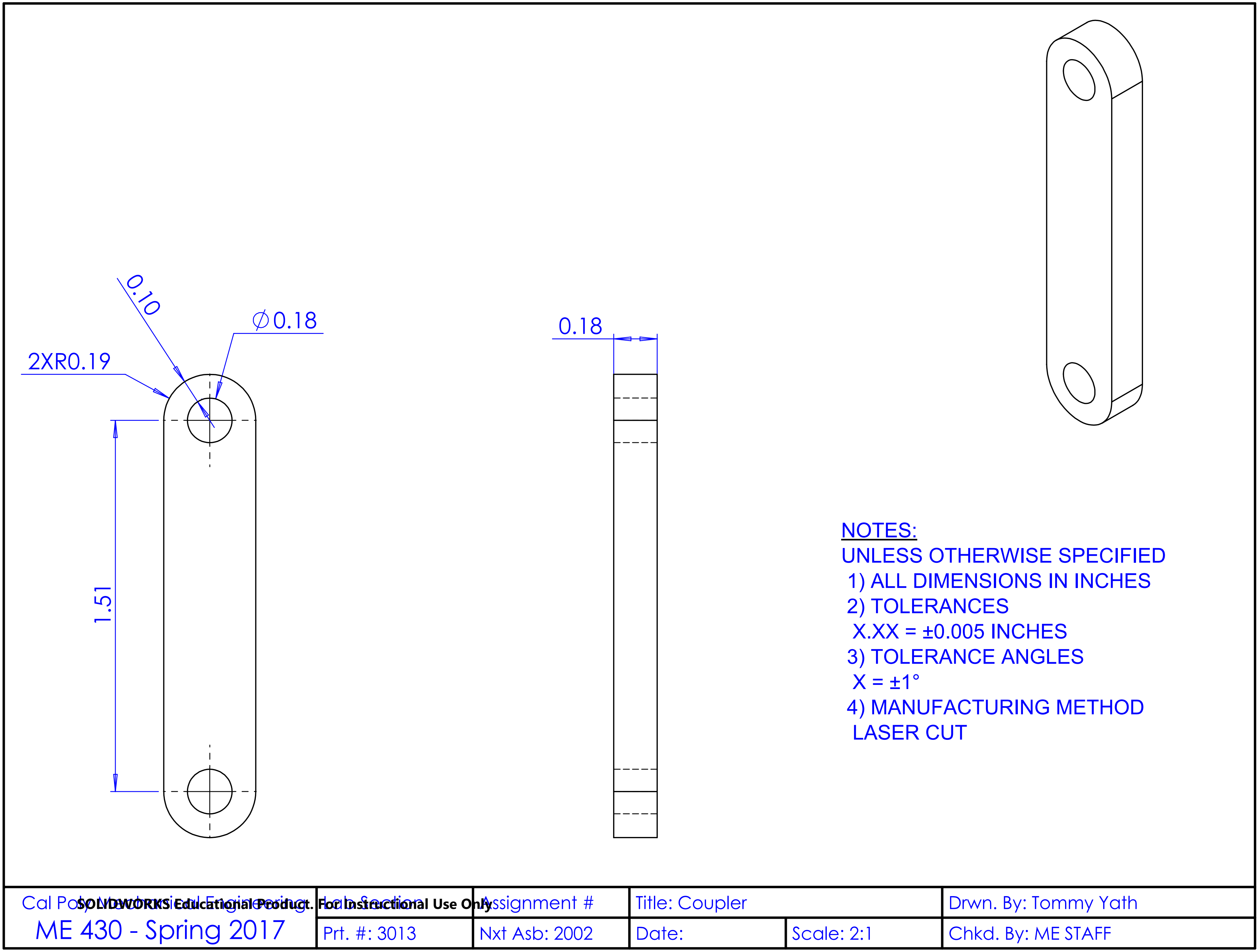


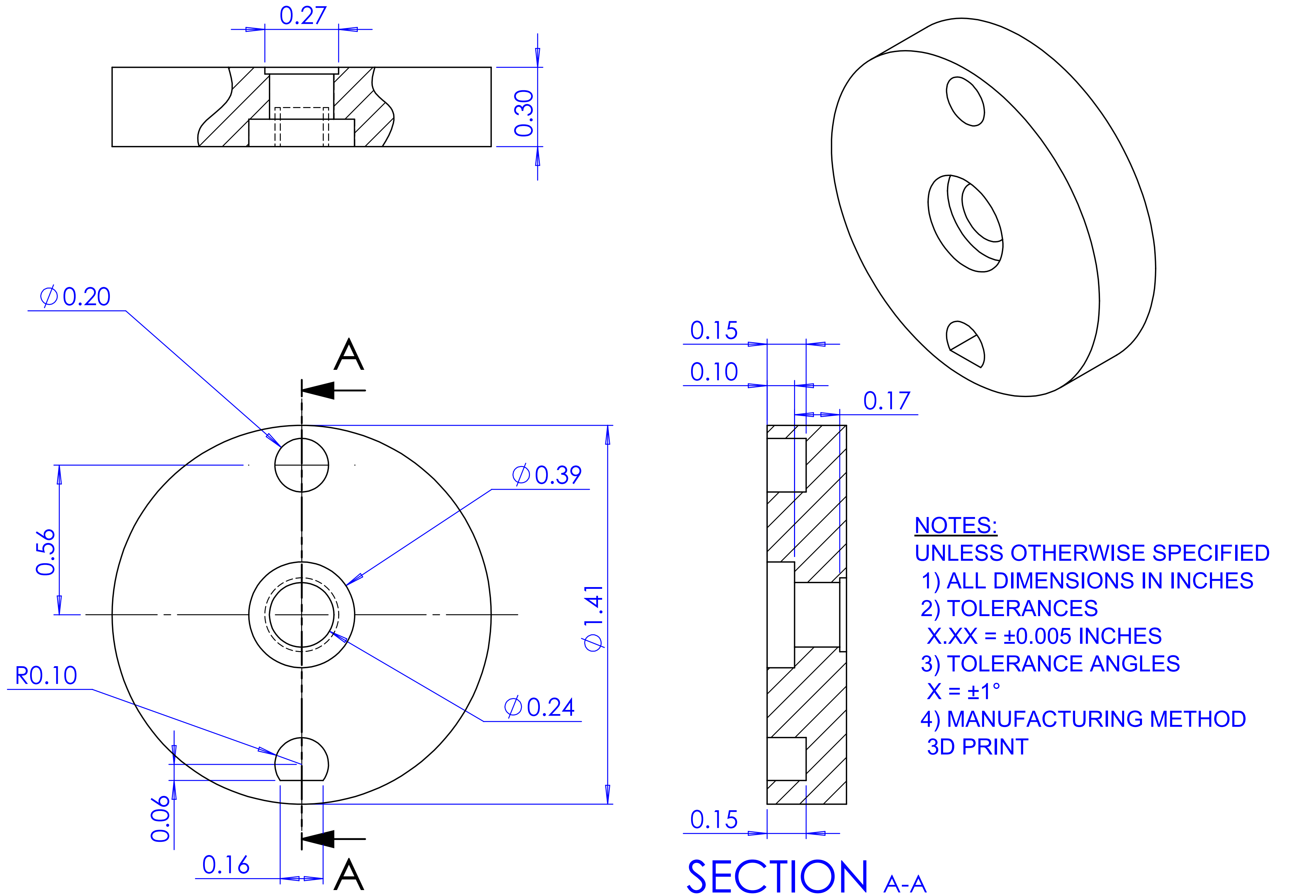




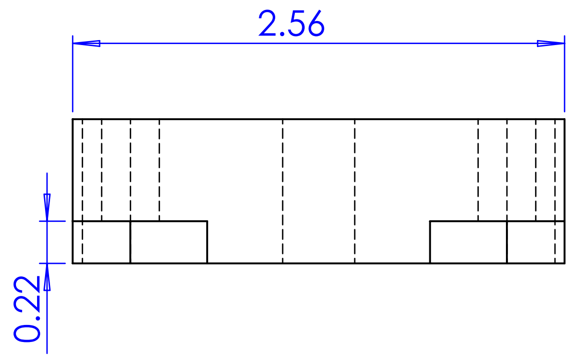


Appendix B. Part Drawings

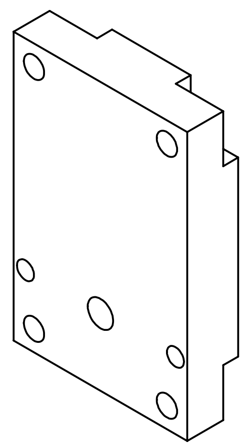


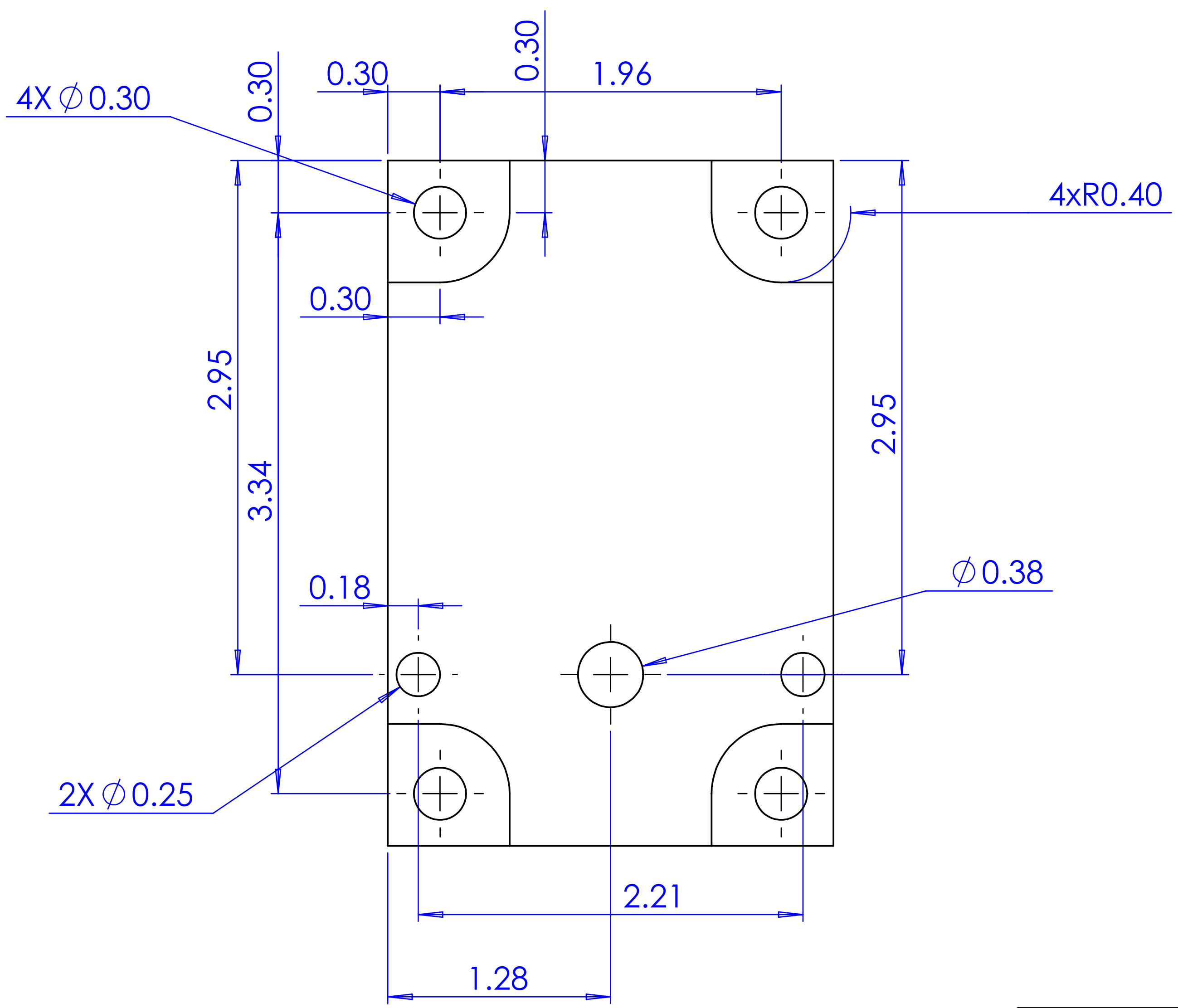


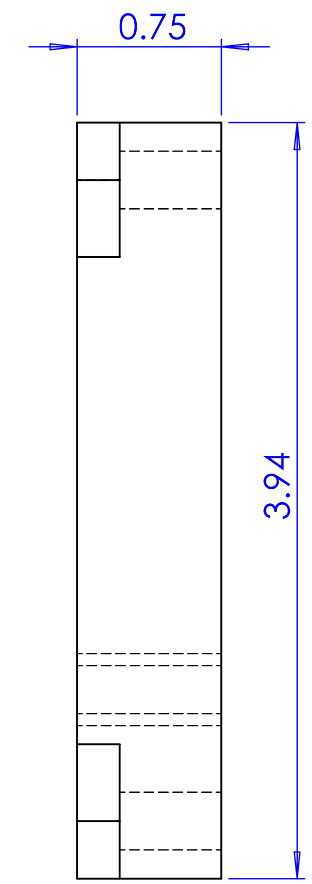
Cal Poly Mechanical Engineering	Lab Section	Assignment #	Title: Crank Disc		Drwn. By: Tommy Yath
ME 430 - Spring 2017	Prt. #: 3011	Nxt Asb: 2002	Date:	Scale: 2:1	Chkd. By: ME STAFF



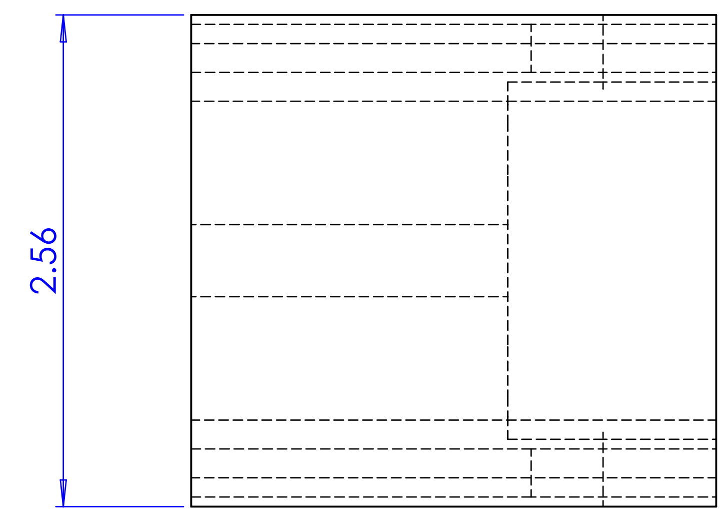
NOTES:
UNLESS OTHERWISE SPECIFIED
1) ALL DIMENSIONS IN INCHES
2) TOLERANCES
X.XX = ±0.005 INCHES
3) TOLERANCE ANGLES
X = ±1°
4) MANUFACTURING METHOD
CNC MACHINED



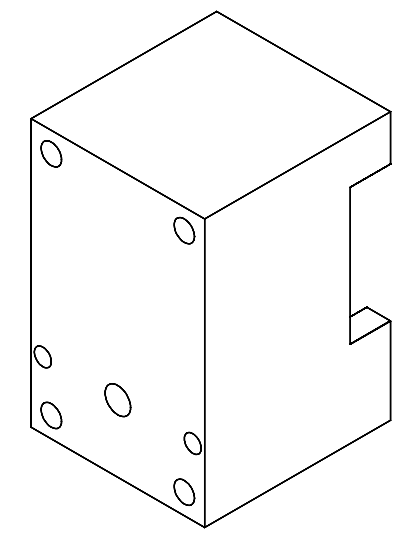


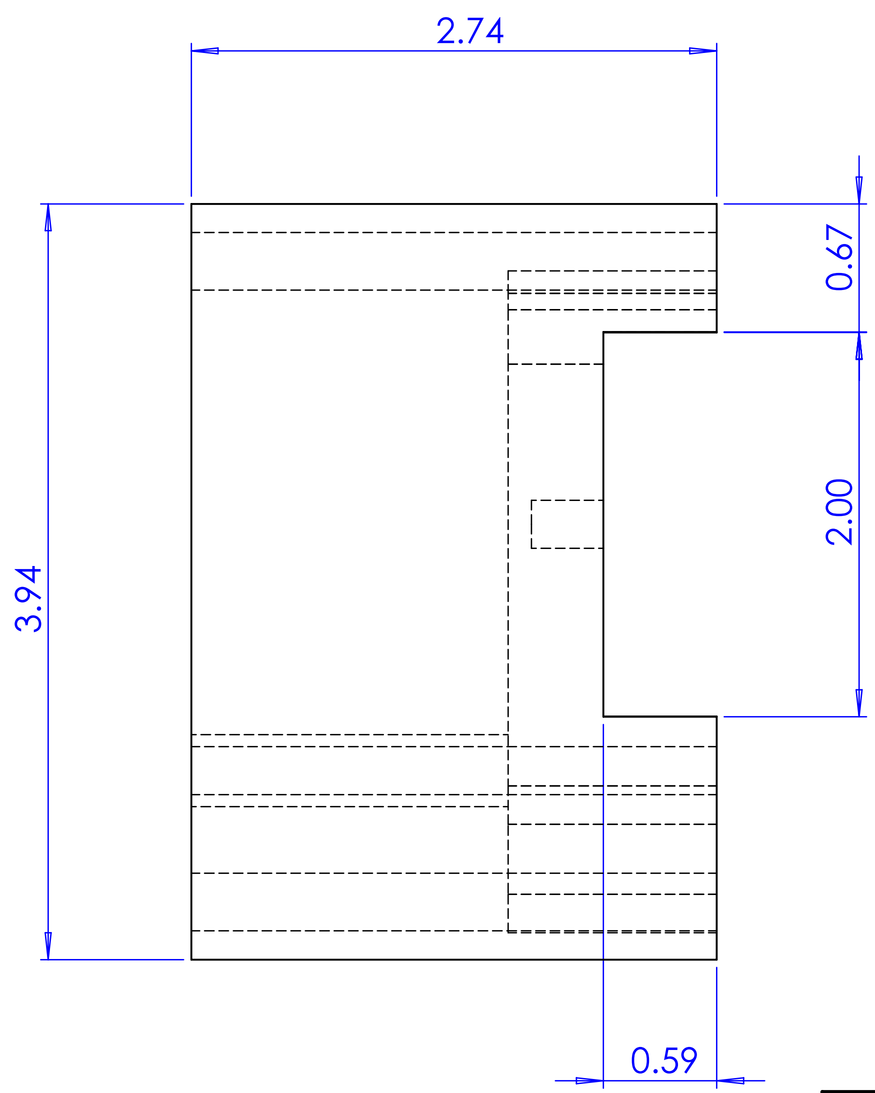


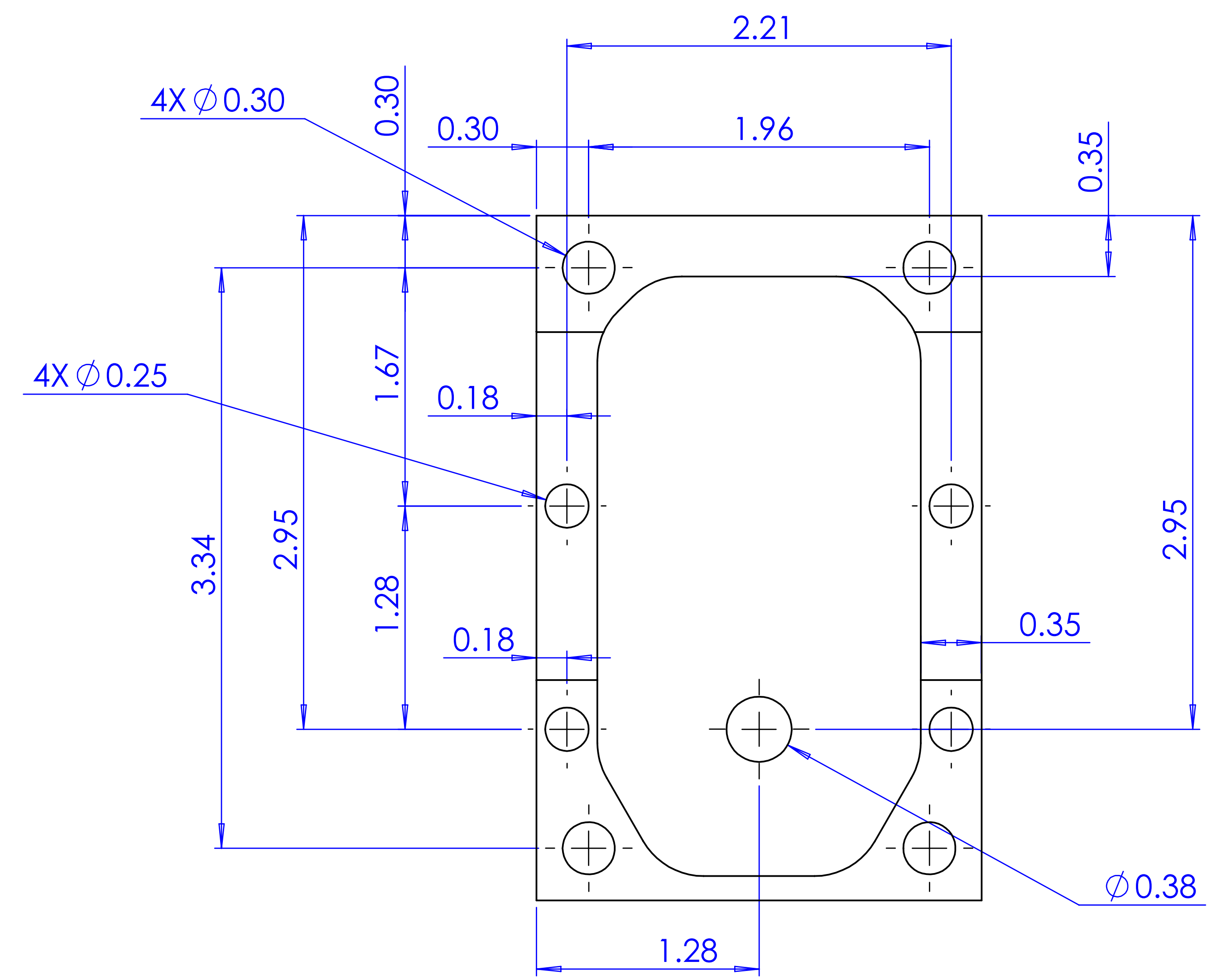
Cal Poly Mechanical Engineering	Lab Section:	Assignment #	Title: Modular End Cap	Drwn. By: Tommy Yath
ME 430 - Spring 2017	Prt. #: 3004	Nxt Asb:	Date: / Scale: 1:1	Chkd. By: ME STAFF



NOTES:
UNLESS OTHERWISE SPECIFIED
1) ALL DIMENSIONS IN INCHES
2) TOLERANCES
X.XX = ±0.005 INCHES
3) TOLERANCE ANGLES
X = ±1°
4) MANUFACTURING METHOD
CNC MACHINED

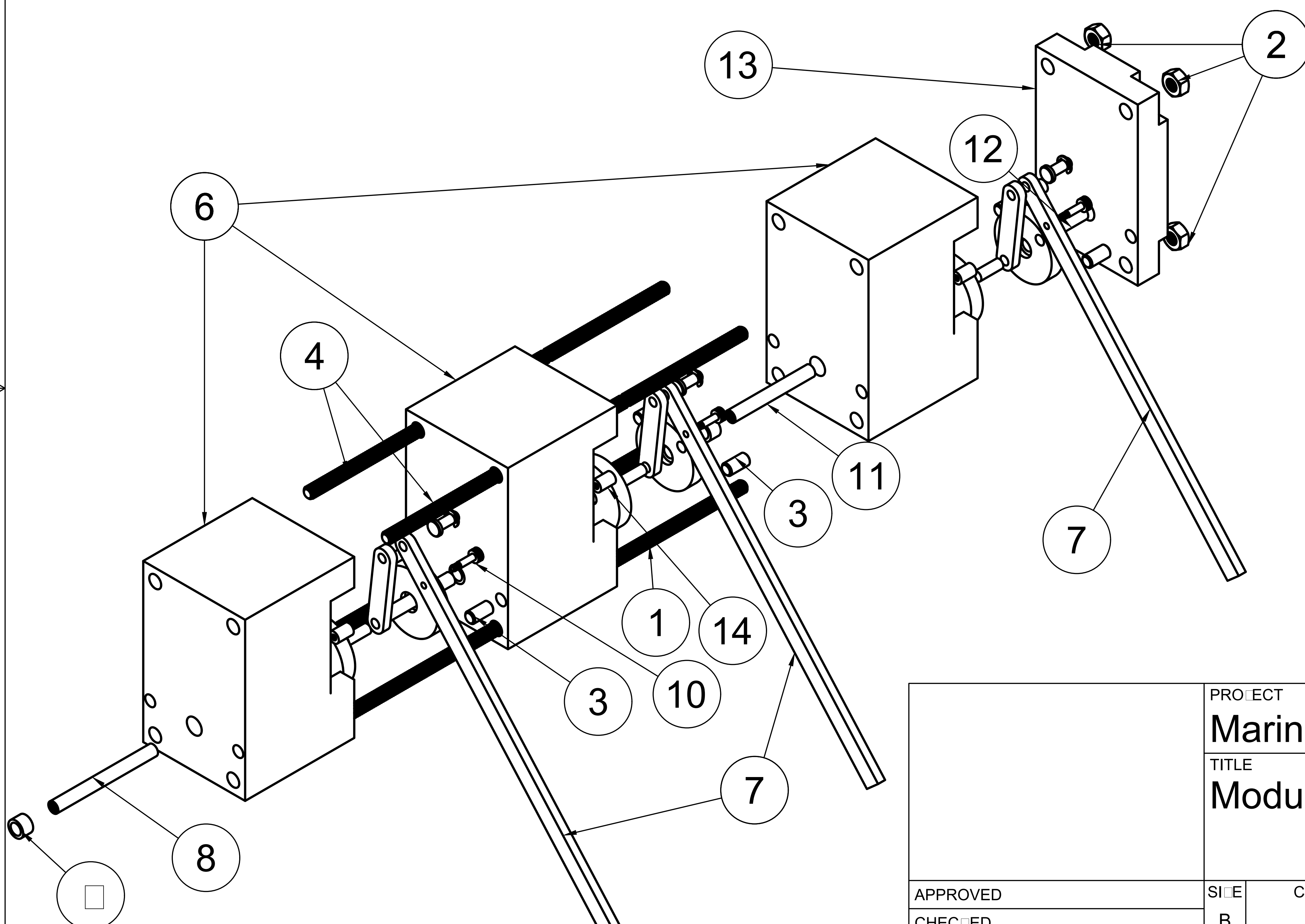




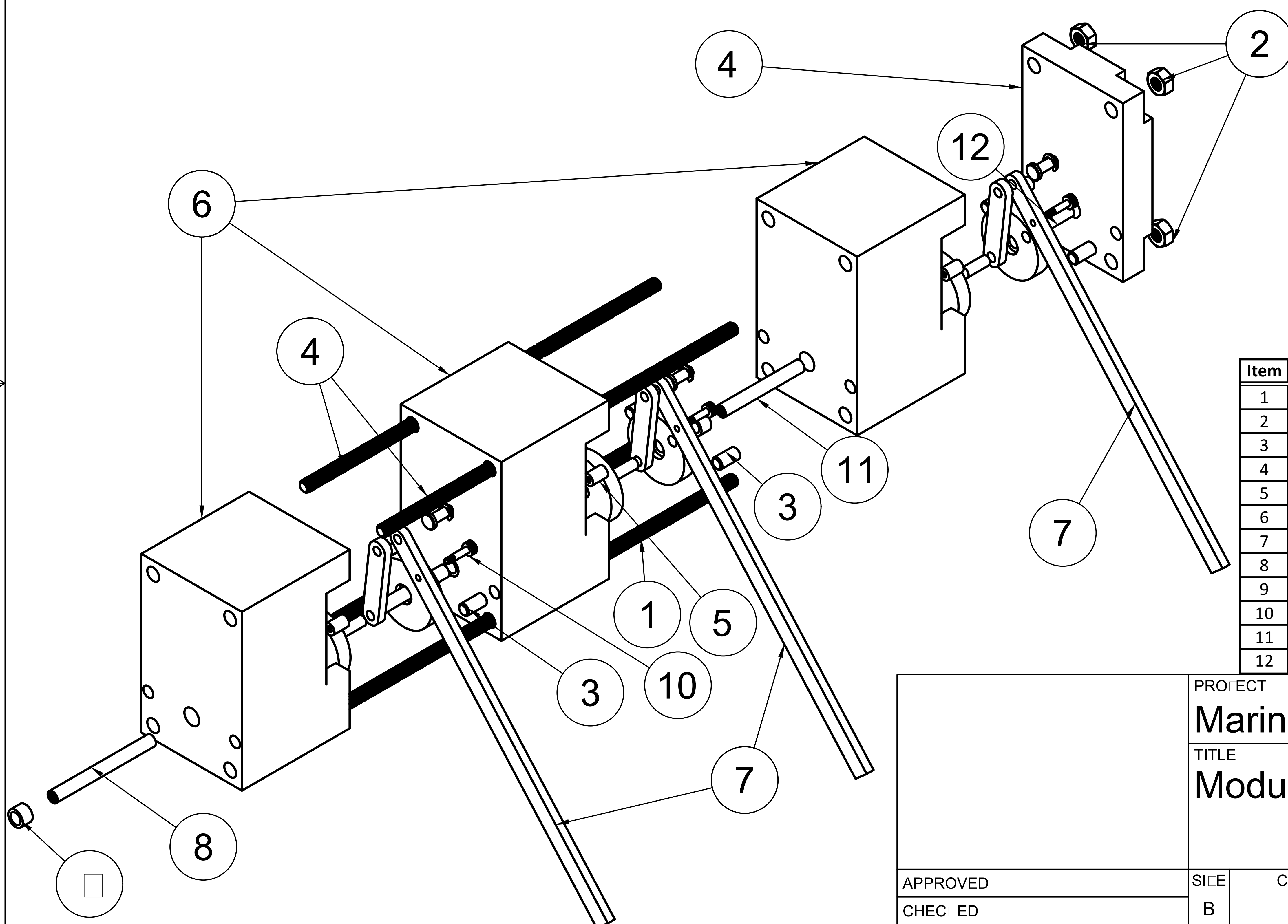


SOLIDWORKS Educational Product. For Instructional Use Only

Cal Poly Mechanical Engineering ME 430 - Spring 2017	Lab Section:	Assignment #	Title: Modular Housing	Drwn. By: Tommy Yath
	Prt. #:	Nxt Asb: 2001	Date: / Scale: 1:1	Chkd. By: ME STAFF



	PROJECT Marine Gastrobot			
	TITLE Modular Transmission Housing			
APPROVED	SIZE B	CODE	DWG NO	REV
CHECKED				
DRAWN Thomas Yath	SCALE 1:2	WEIGHT	SHEET 1/1	



Item	Part Number	Description	Quantity
1	3009	Through Bolt Rod	4
2	3010	Through Bolt Nut	6
3	3008	Alignment Pin	6
4	3004	Modular Endcap	1
5	3006	Threaded Insert	3
6	3003	Modular Housing	3
7	2002	Drive Train Assembly	3
8	3036	Drive Shaft	1
9	3005	Sleeve Bearing	4
10	3007	Shoulder Bolt	3
11	3035	Connecting Shaft	2
12	3037	End Shaft	1

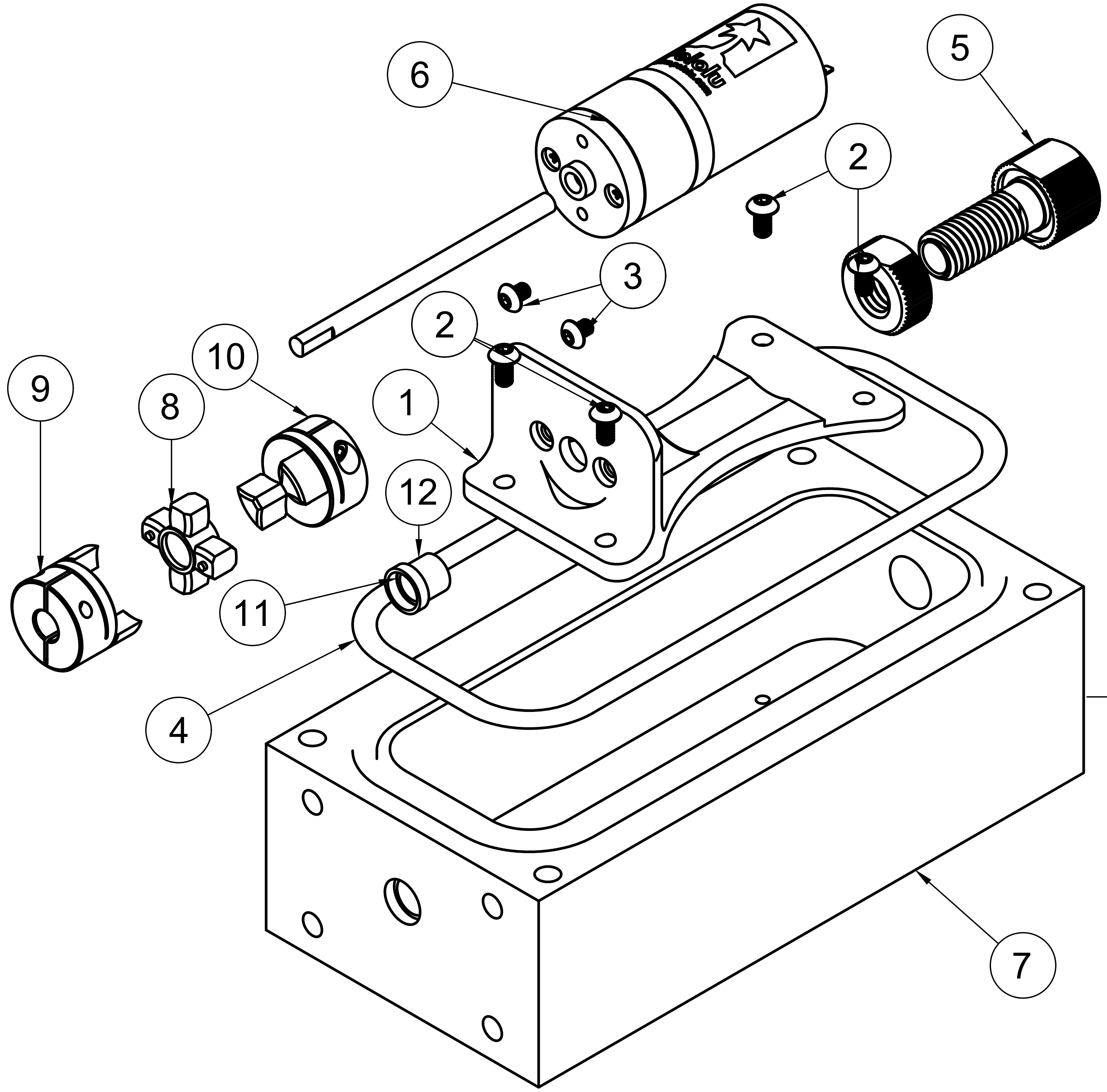
PRO□ECT

Marine Gastrobot

TITLE

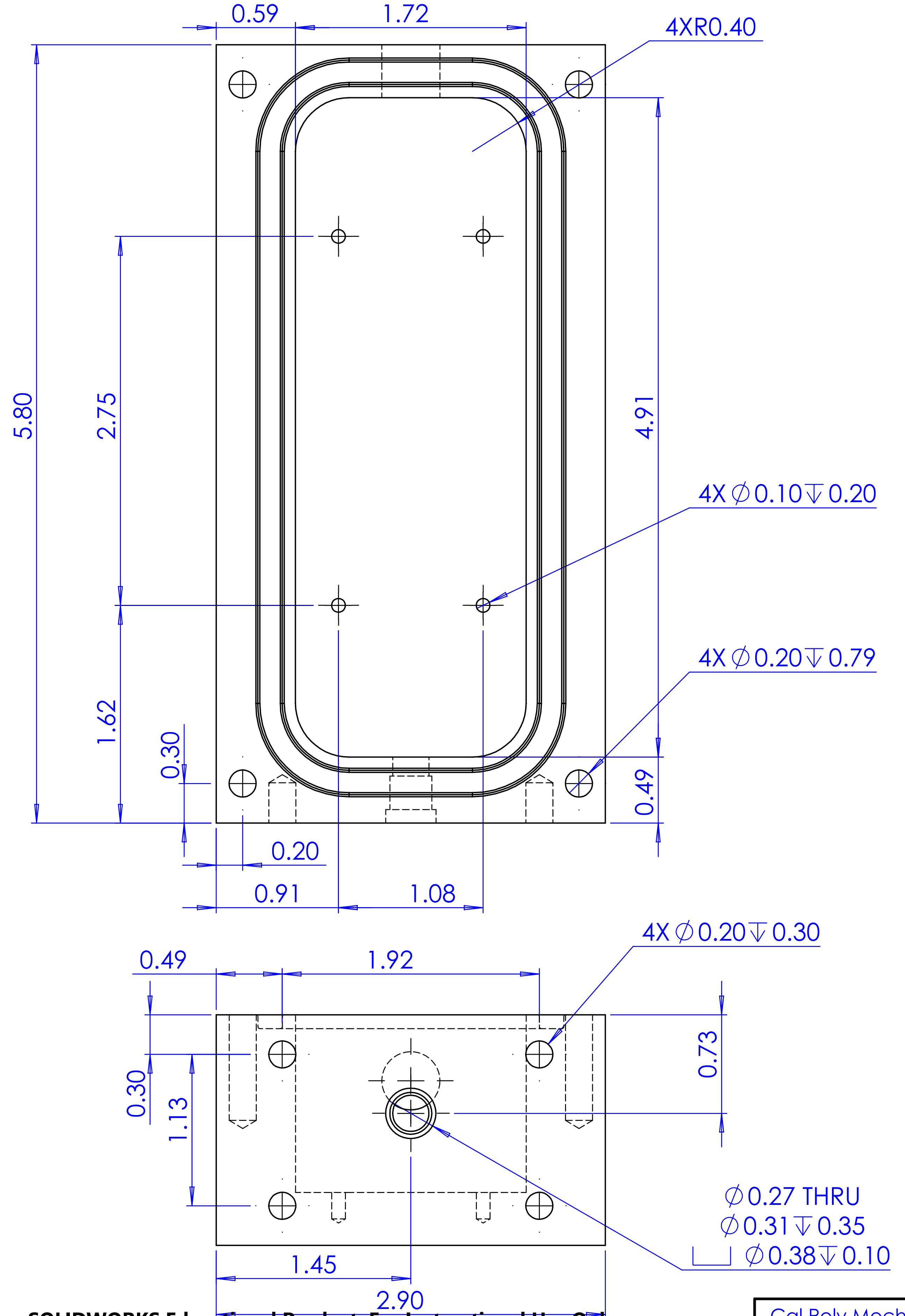
Modular Transmission Housing

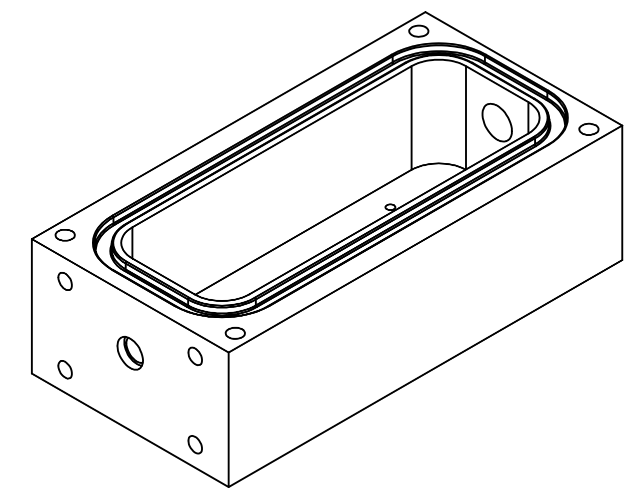
APPROVED	SI□E	CODE	DWG NO	REV
CHEC□ED	B			
DRAWN Thomas Yath	SCALE 1□2	WEIGHT	SHEET 1/1	



Item	Part Number	Description	Quantity
1	3020	Motor Mount	1
2	3029	5-40 x 0.25in Length BHCS	4
3	3028	M3x0.5mm x 4mm Length SHCS	2
4	3024	O-Ring	1
5	3025	Wire Pass Through Connector	1
6	3019	Motor	1
7	3017	Motor Housing Bottom	1
8	3022	Spider	1
9	3023	1/4in Shaft Coupler Hub	1
10	3021	4mm Shaft Coupler Hub	1
11	3027	Dynamic Shaft Seal	1
12	3026	Sleeve Bearing	1

Dept.	Technical reference	Created by	Approved by
		Thomas Yath 6/11/2017	
		Document type	Document status
		Title: Motor Housing Assembly	DWG No.
			Rev. / Date of issue / Sheet 1/1





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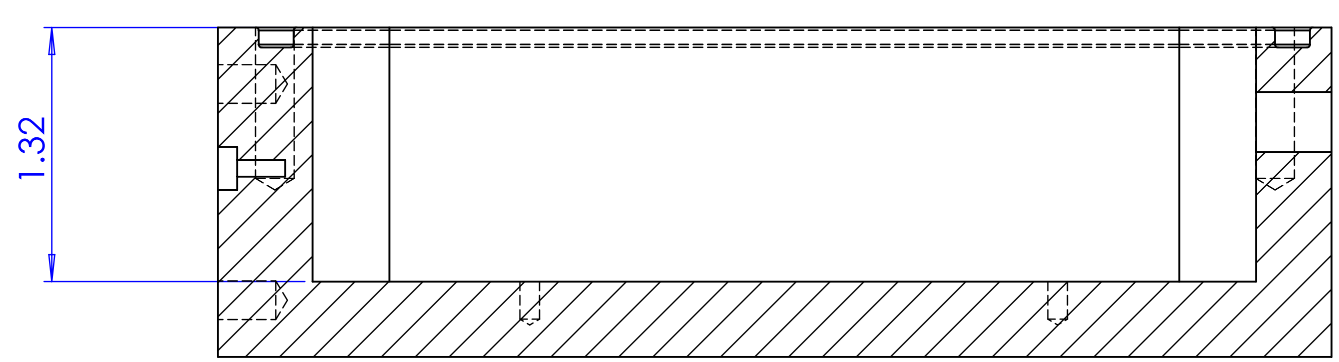
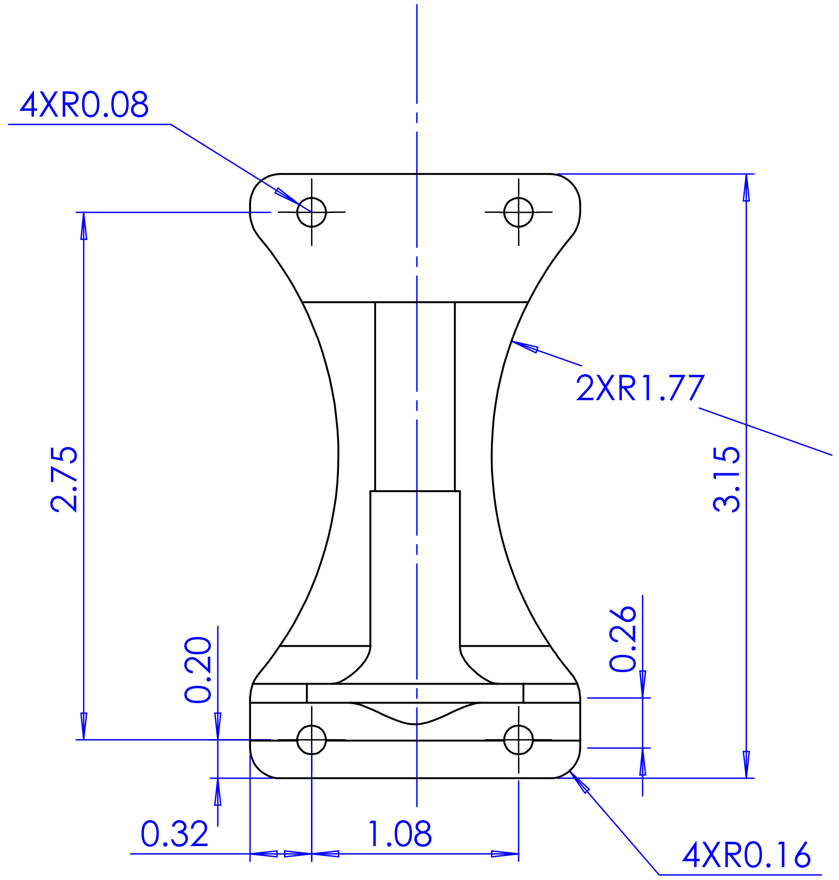
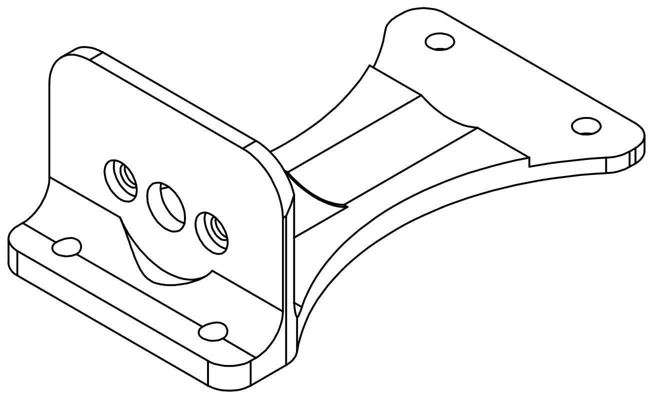
X = ±1°
4) MANUFACTURING METHOD
CNC MACHINED

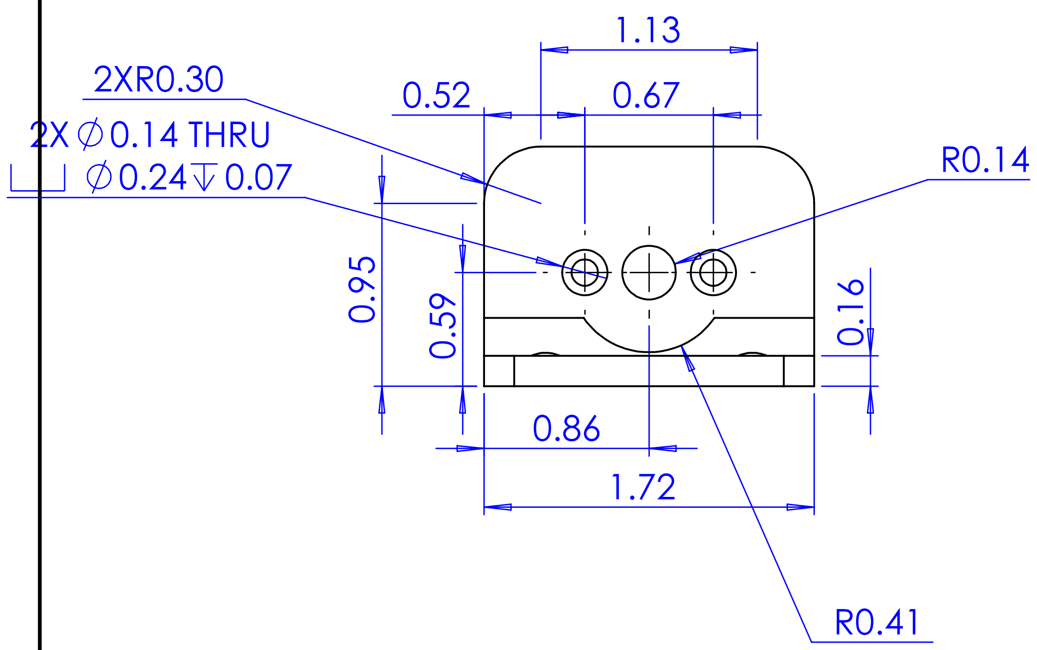


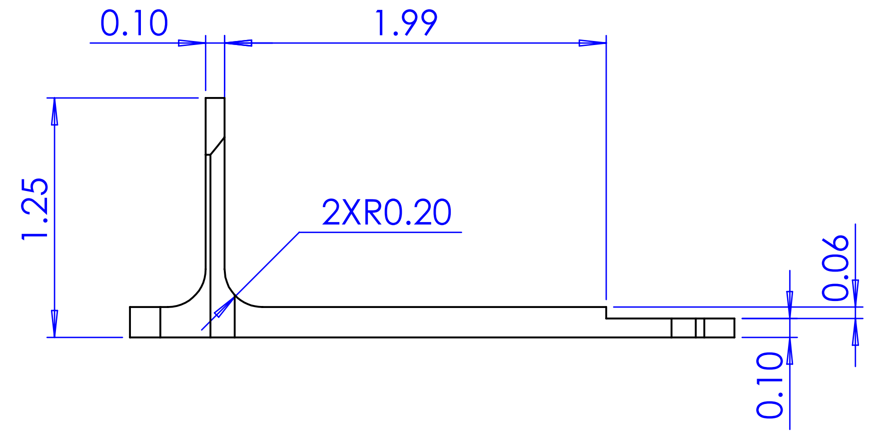
Cal Poly Mechanical Engineering	Lab Section:	Assignment #	Title: Motor Housing		Drwn. By: Tommy Yath
ME 430 - Spring 2017	Prt. #: 3017	Nxt Asb: 2003	Date:	Scale: 1:1	Chkd. By: ME STAFF



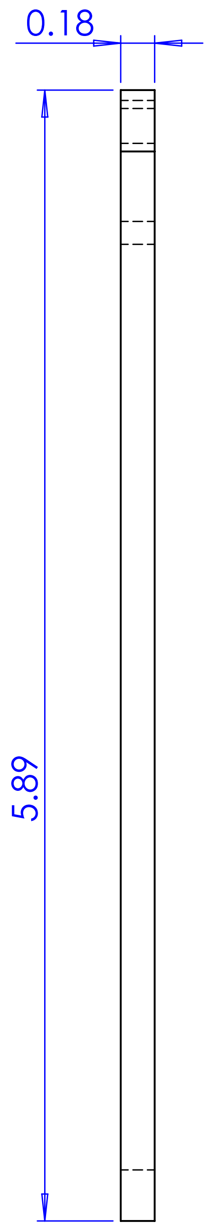
NOTES:
UNLESS OTHERWISE SPECIFIED
1) ALL DIMENSIONS IN INCHES
2) TOLERANCES
X.XX = ±0.005 INCHES
3) TOLERANCE ANGLES
X = ±1°
4) MANUFACTURING METHOD
3D PRINTING

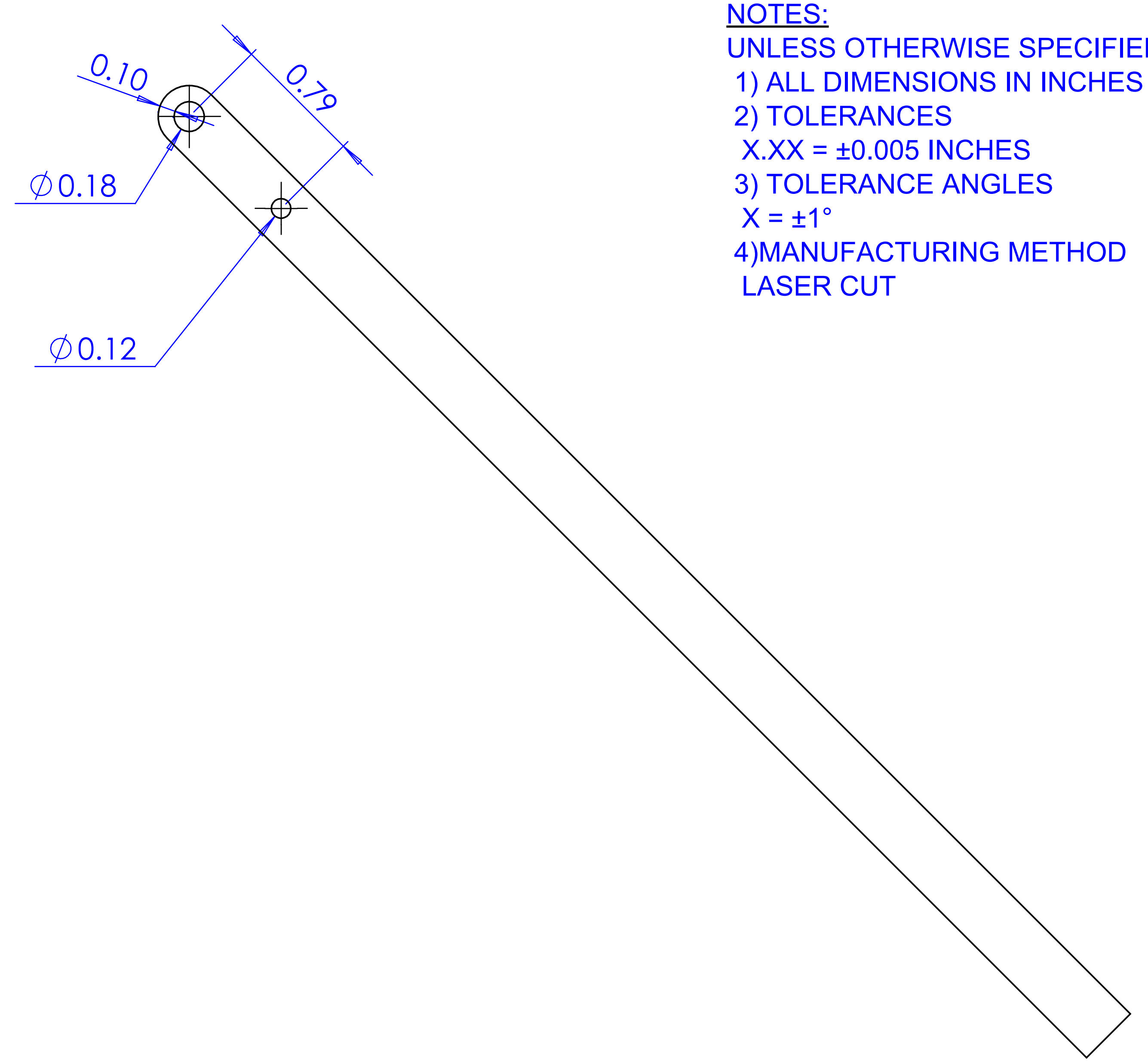


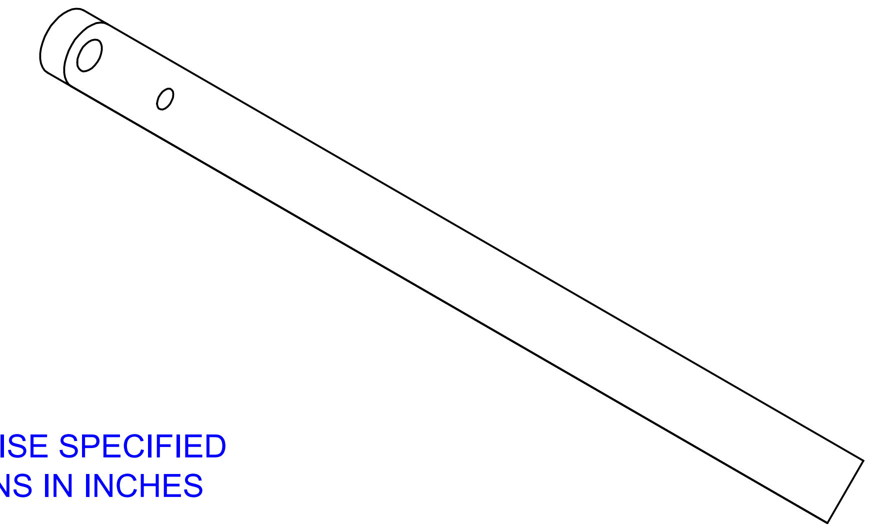




Cal Poly Mechanical Engineering	Lab Section:	Assignment #	Title: Motor Mount	Drwn. By: Tommy Yath
ME 430 - Spring 2017	Prt. #: 3020	Nxt Asb: 2003	Date: Scale: 1:1	Chkd. By: ME STAFF





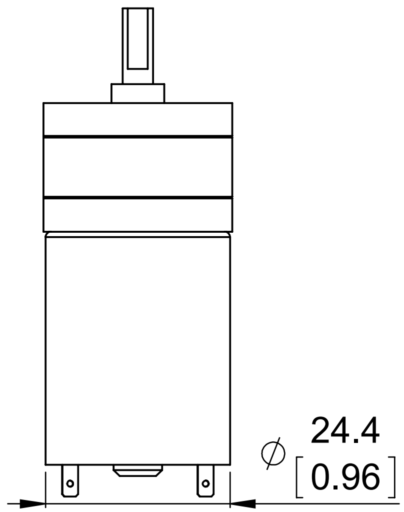


NOTES:
UNLESS OTHERWISE SPECIFIED
1) ALL DIMENSIONS IN INCHES
2) TOLERANCES
X.XX = ±0.005 INCHES
3) TOLERANCE ANGLES
X = ±1°
4)MANUFACTURING METHOD
LASER CUT

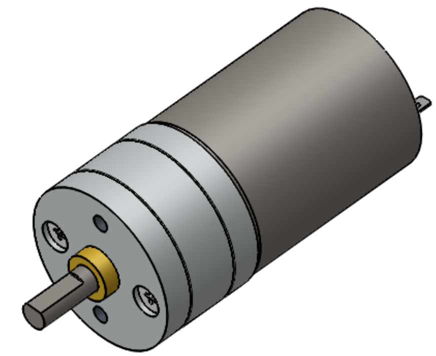
Cal Poly Mechanical Engineering	Lab Section:	Assignment #	Title: Rocker		Drwn. By: Tommy Yath
ME 430 - Spring 2017	Prt. #: 3015	Nxt Asb: 2002	Date:	Scale: 1:1	Chkd. By: ME STAFF

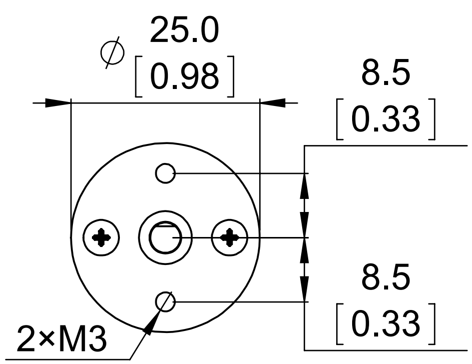
Appendix C. Vendor Information

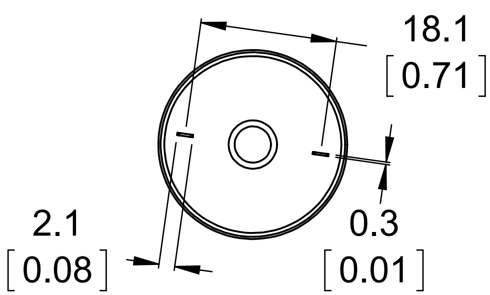
1. Digi-Key Electronics
    a. Total Purchases Cost (including shipping): $52.77
    b. Contact Information:
        i. E-mail: sales@digikey.com
        ii. Phone: (218) 681-6674
2. Home Depot
    a. Total Purchases Cost (including taxes): $16.99
    b. Contact Information
        i. Address: 1551 Froom Ranch Way, San Luis Obispo, CA 93405
        ii. Phone: (805) 596-0857
3. McMaster-Carr
    a. Total Purchases Cost: $879.72
    b. Contact Info:
        i. E-mail: la.sales@mcmaster.com
        ii. Phone: (562) 692-5911
4. Pololu Robotics & Electronics
    a. Total Purchases Cost (including shipping): $53.85
    b. Contact Info:
        i. E-mail: support@pololu.com
        ii. Phone (concerning changing order): (702) 262-6648
5. PolyCase
    a. Total Purchases Cost: $211.75
    b. Contact Info:
        i. E-mail: sales@polycase.com
        ii. Phone: 1-800-248-1233

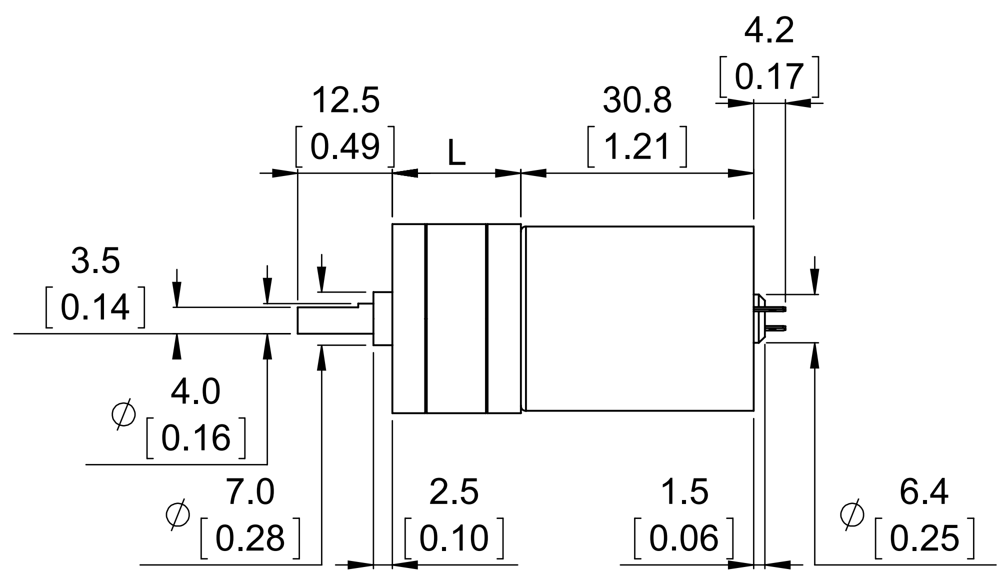


Gear ratio	L
4.4:1	17 mm [0.68 in]
9.7:1	17 mm [0.68 in]
20.4:1	19 mm [0.75 in]
34:1	21 mm [0.83 in]
47:1	21 mm [0.83 in]
75:1	23 mm [0.91 in]
99:1	23 mm [0.91 in]
172:1	25 mm [0.98 in]
227:1	25 mm [0.98 in]
378:1	27 mm [1.06 in]
499:1	27 mm [1.06 in]









1. To get the specified scale, select 100% in print settings.

Scale: 1:1

https://www.pololu.com/category/115/25d-mm-gearmotors

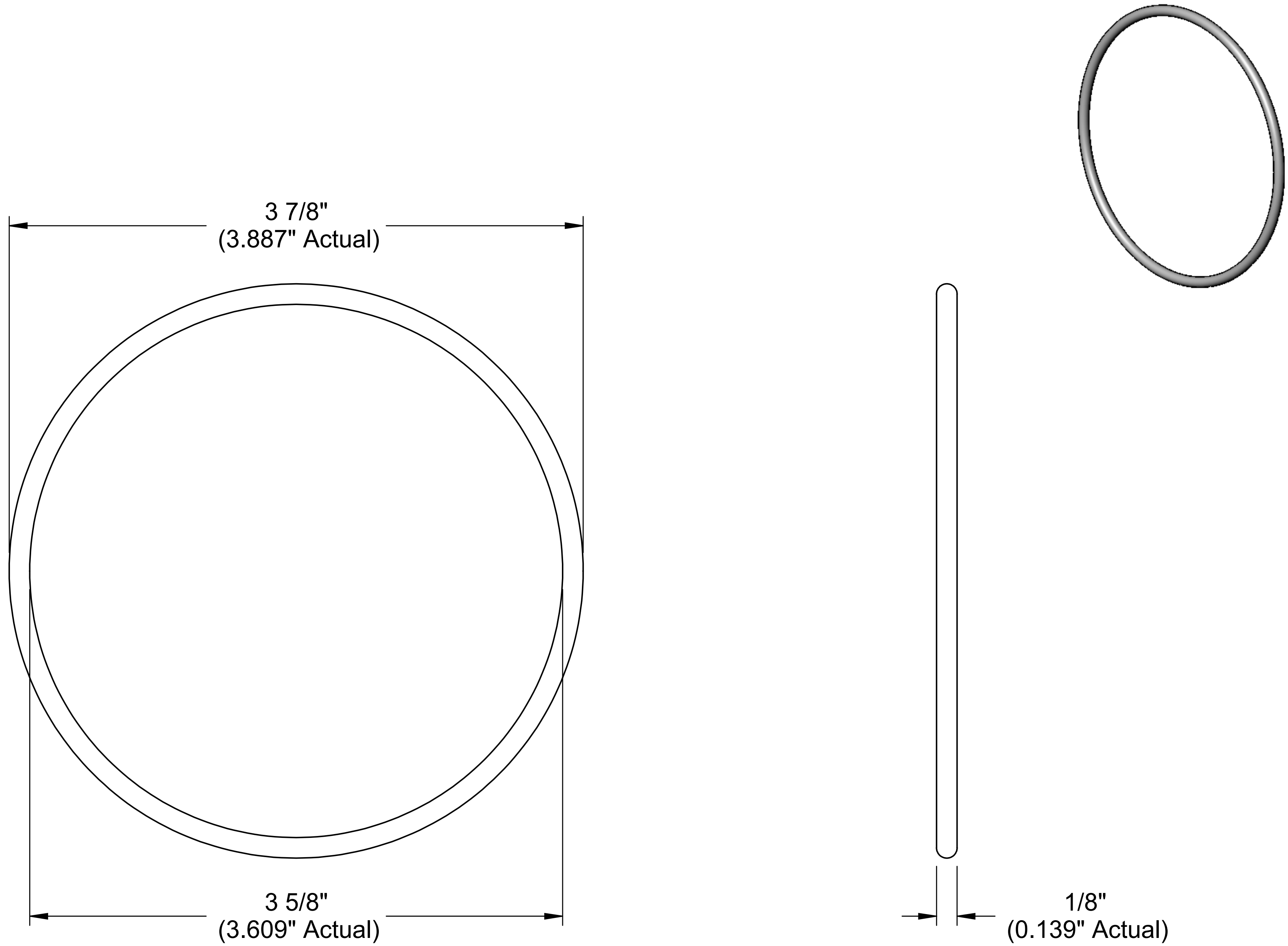
Name:
25D mm Metal Gearmotors (without encoders)

Drawing date:
15 January 2016

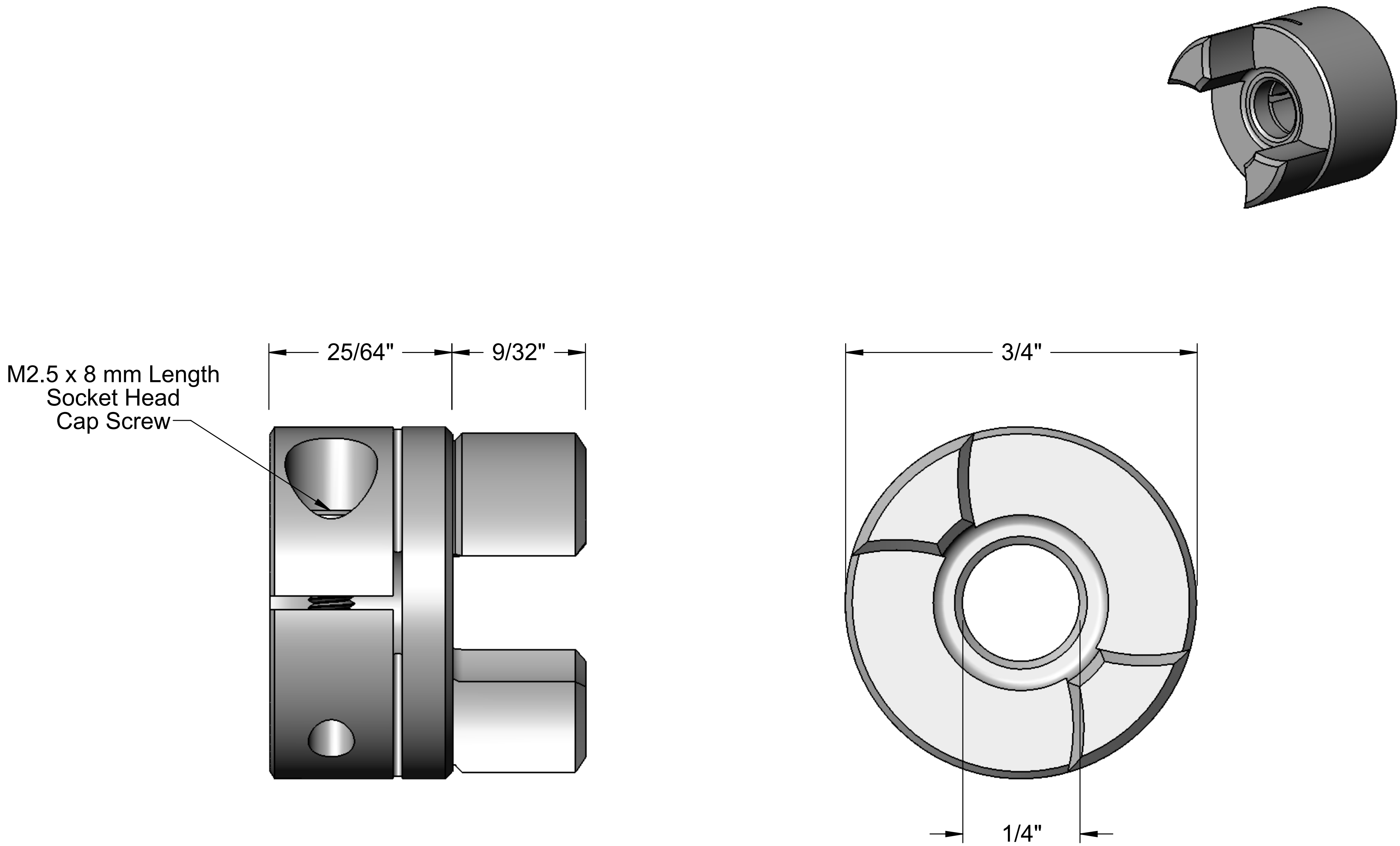
Units: mm [in]

Material: mix

Pololu Robotics & Electronics

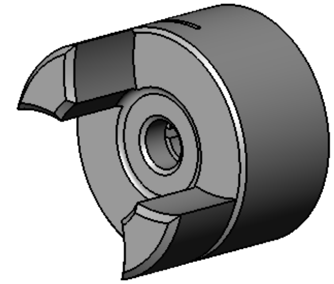


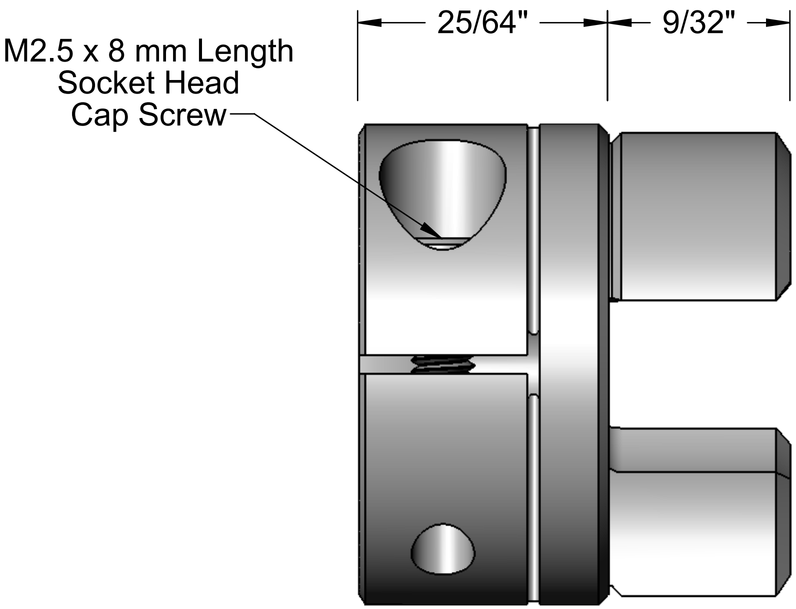
McMASTER-CARR® CAD	PART NUMBER	9452K189
http://www.mcmaster.com Information in this drawing is provided for reference only.	Multipurpose O-Ring	

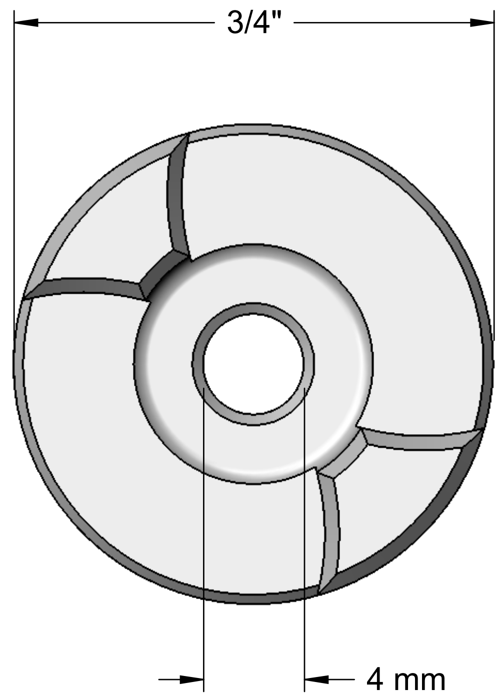


Complete Coupling (Two Hubs and One Spider) Overall Length 1.1"

McMASTER-CARR® CAD	PART NUMBER 9845T102
http://www.mcmaster.com © 2013 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	Coupling Hub for Zero-Backlash Replaceable-Center Flexible Shaft Coupling

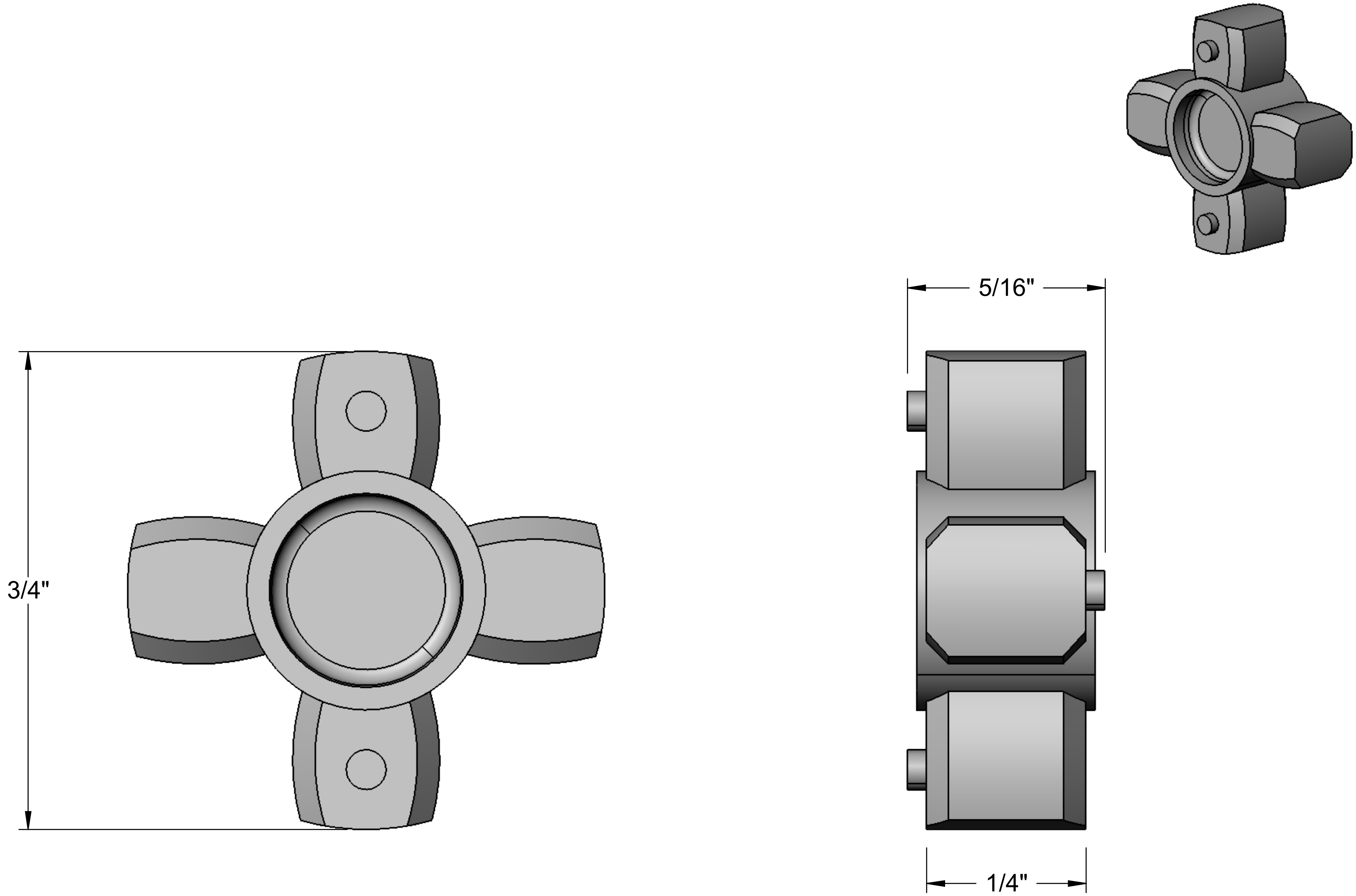




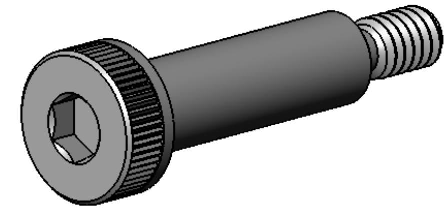


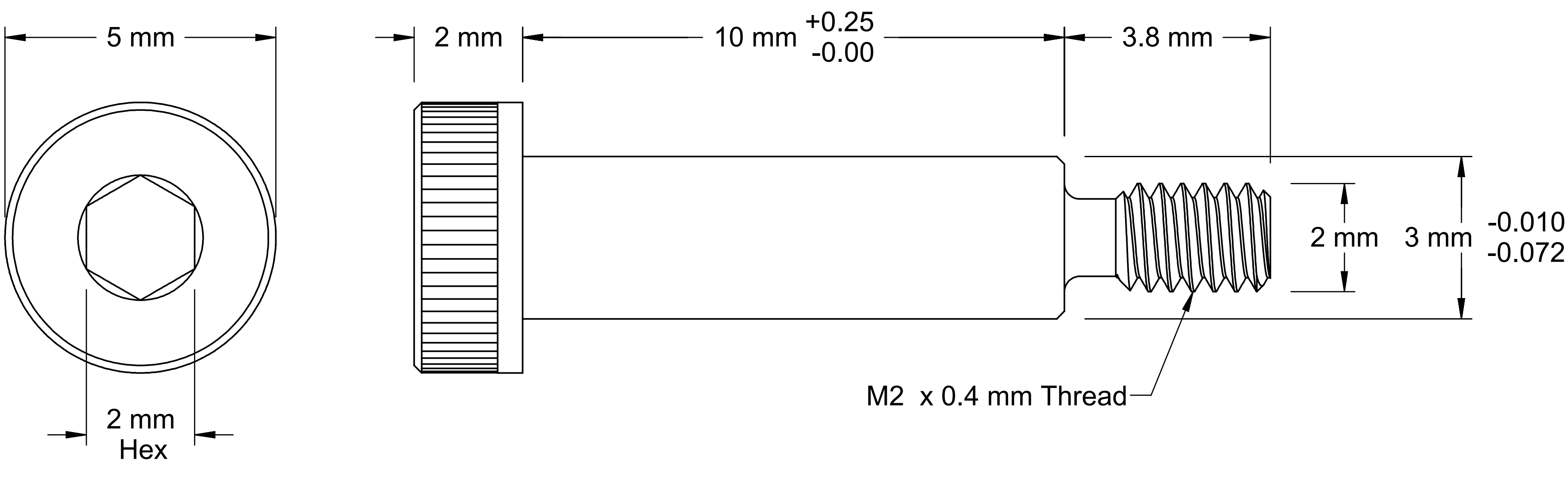
Complete Coupling (Two Hubs and One Spider) Overall Length 1.1"

McMASTER-CARR® CAD	PART NUMBER	9845T1
http://www.mcmaster.com	Coupling Hub for Zero-Backlash Replaceable-Center Flexible Shaft Coupling	

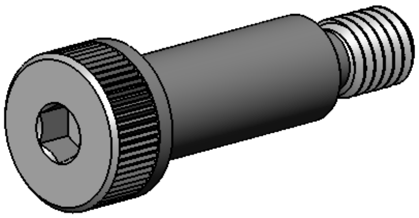


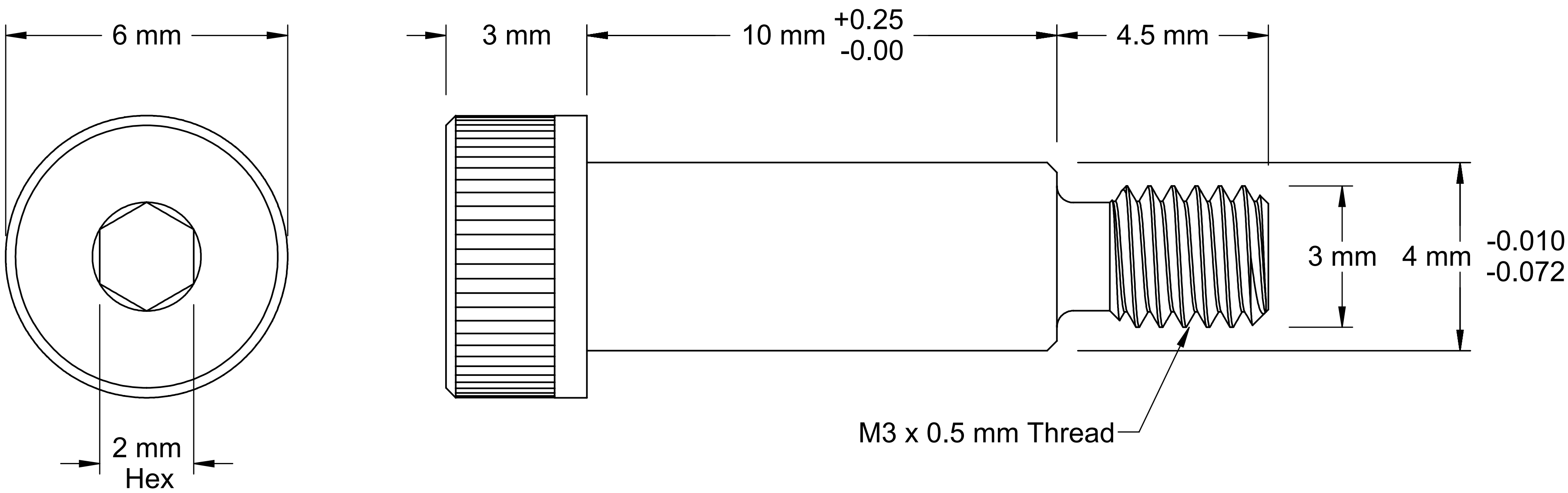
McMASTER-CARR® CAD	PART NUMBER	9845T11
http://www.mcmaster.com © 2013 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	Spider for Zero-Backlash Replaceable-Center Flexible Shaft-Coupling	



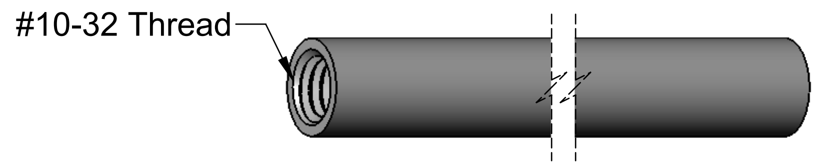


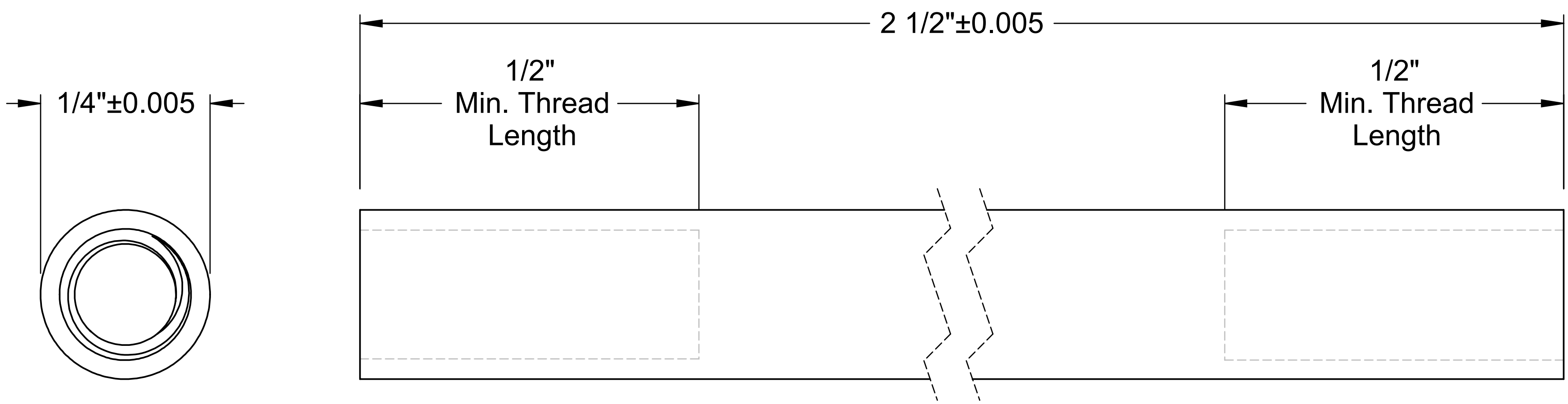
McMASTER-CARR® CAD	PART NUMBER	90265A115
http://www.mcmaster.com Information in this drawing is provided for reference only.	Shoulder Screw	



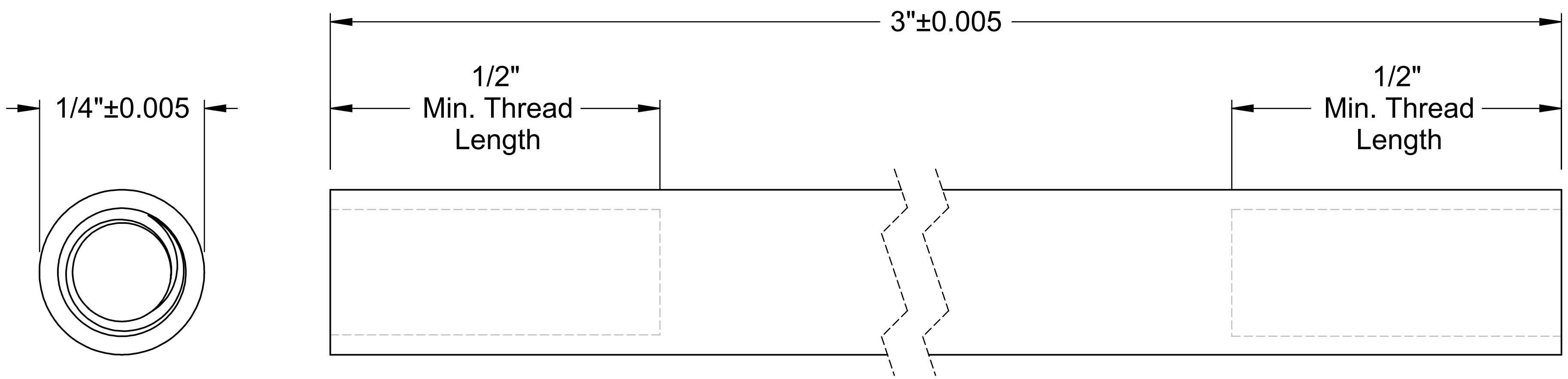


McMASTER-CARR® CAD	PART NUMBER	90265A121
http://www.mcmaster.com 	Shoulder Screw	
Information in this drawing is provided for reference only.		





McMASTER-CARR® CAD	PART NUMBER	91125A033	
http://www.mcmaster.com © 2015 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	Female Threaded Round Standoff		

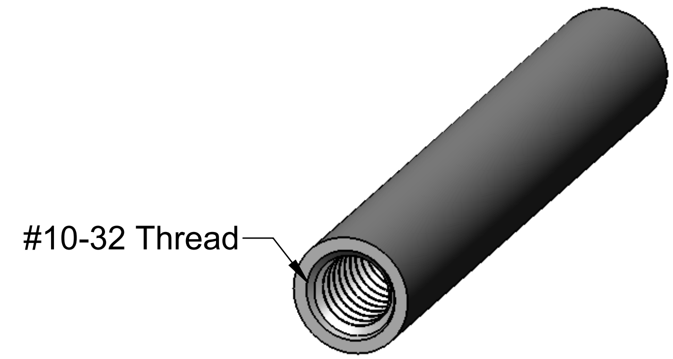


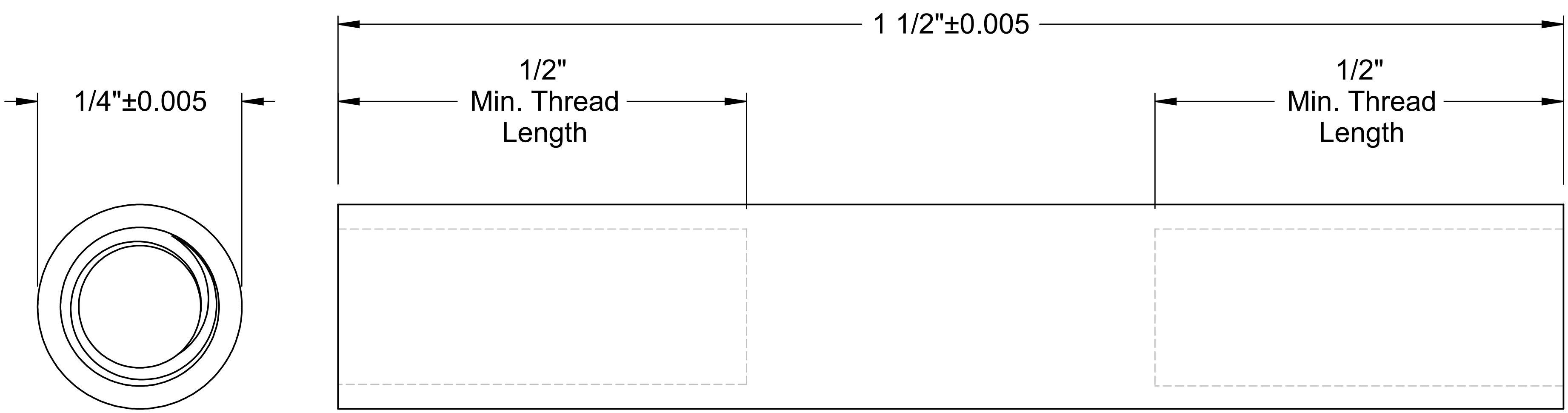
McMASTER-CARR® CAD

PART NUMBER **91125A037**

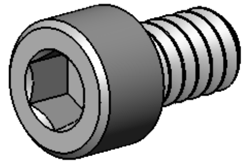
http://www.mcmaster.com

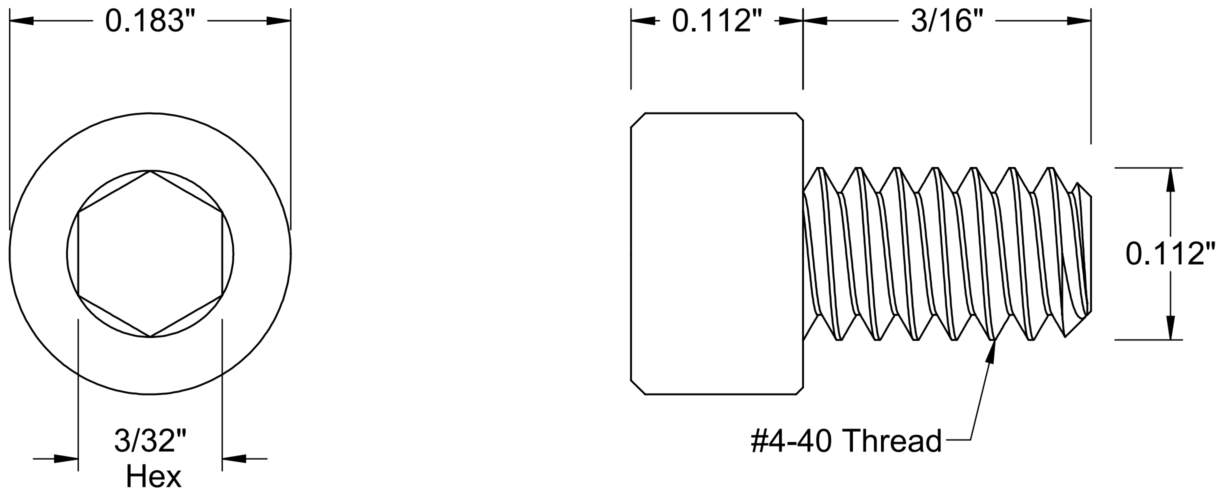
Female Threaded
Round Standoff





McMASTER-CARR® CAD	PART NUMBER	91125A501
http://www.mcmaster.com © 2015 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	Female Threaded Round Standoff	



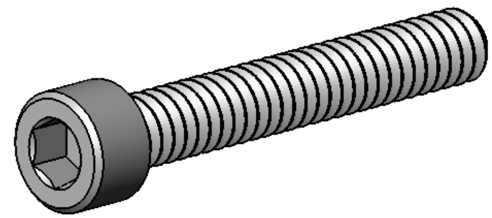


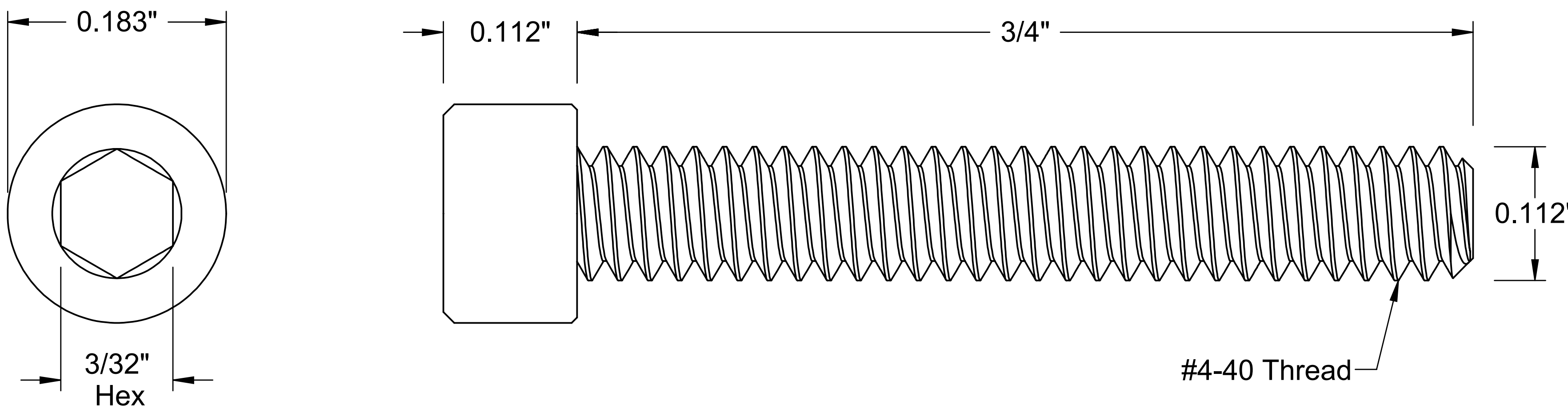
MCMASTER-CARR® CAD

PART NUMBER 92196A105

http://www.mcmaster.com

Stainless Steel
Socket Head Cap Screw



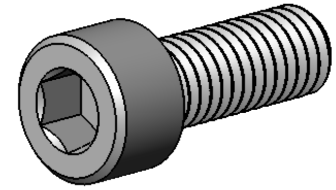


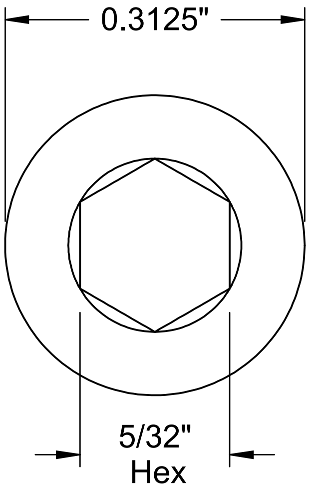
McMASTER-CARR® CAD

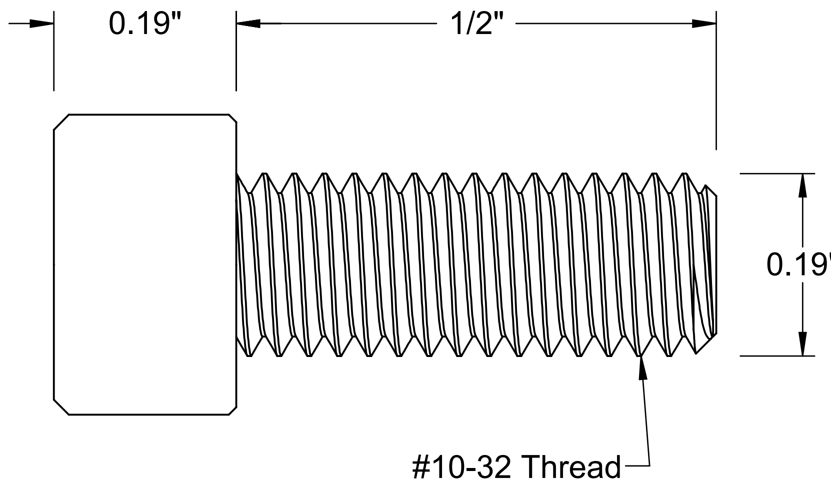
PART NUMBER **92196A113**

http://www.mcmaster.com

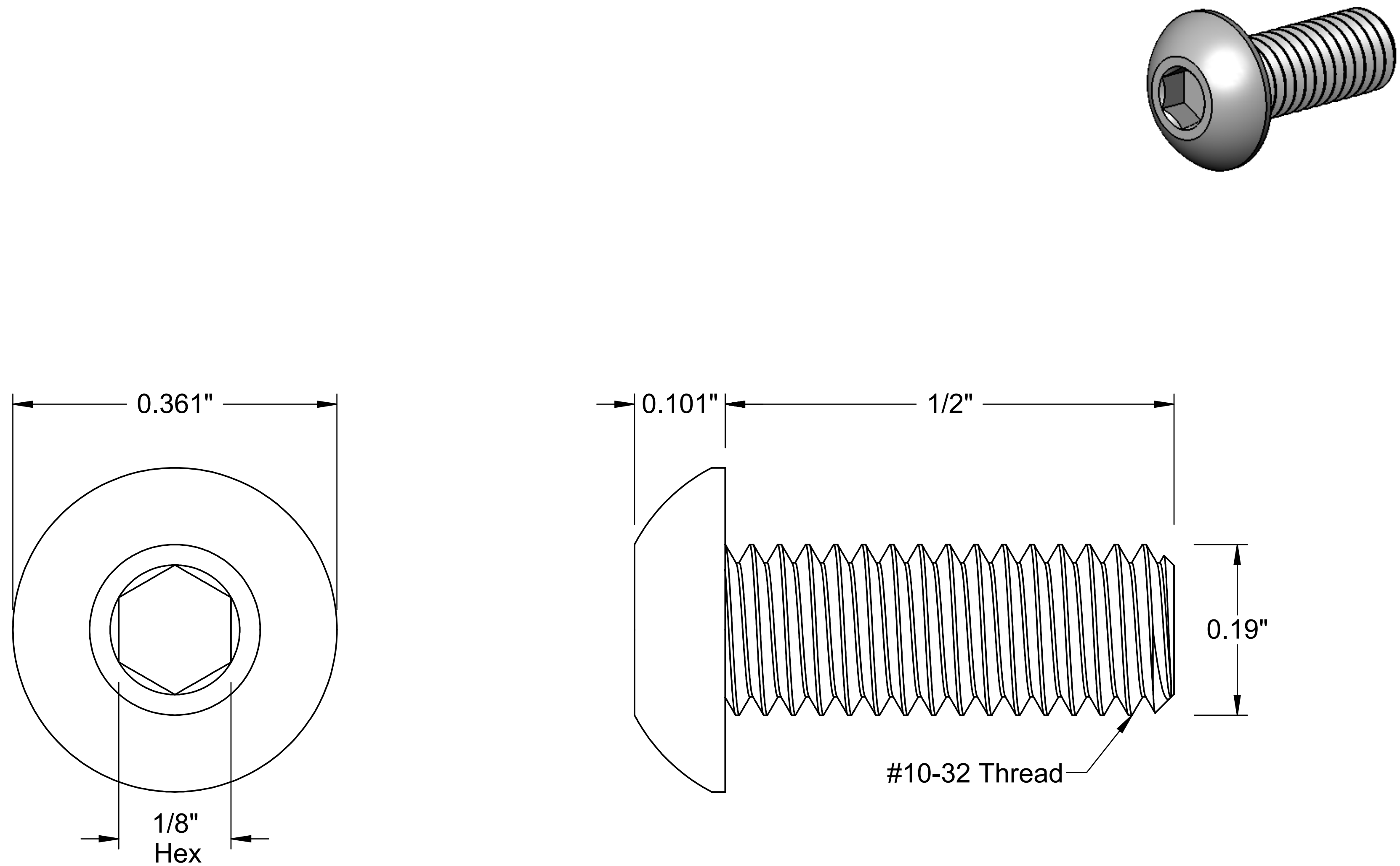
Stainless Steel
Socket Head Cap Screw







McMASTER-CARR® CAD		PART NUMBER	92196A269
http://www.mcmaster.com © 2014 McMaster-Carr Supply Company Information in this drawing is provided for reference only.		Stainless Steel Socket Head Cap Screw	

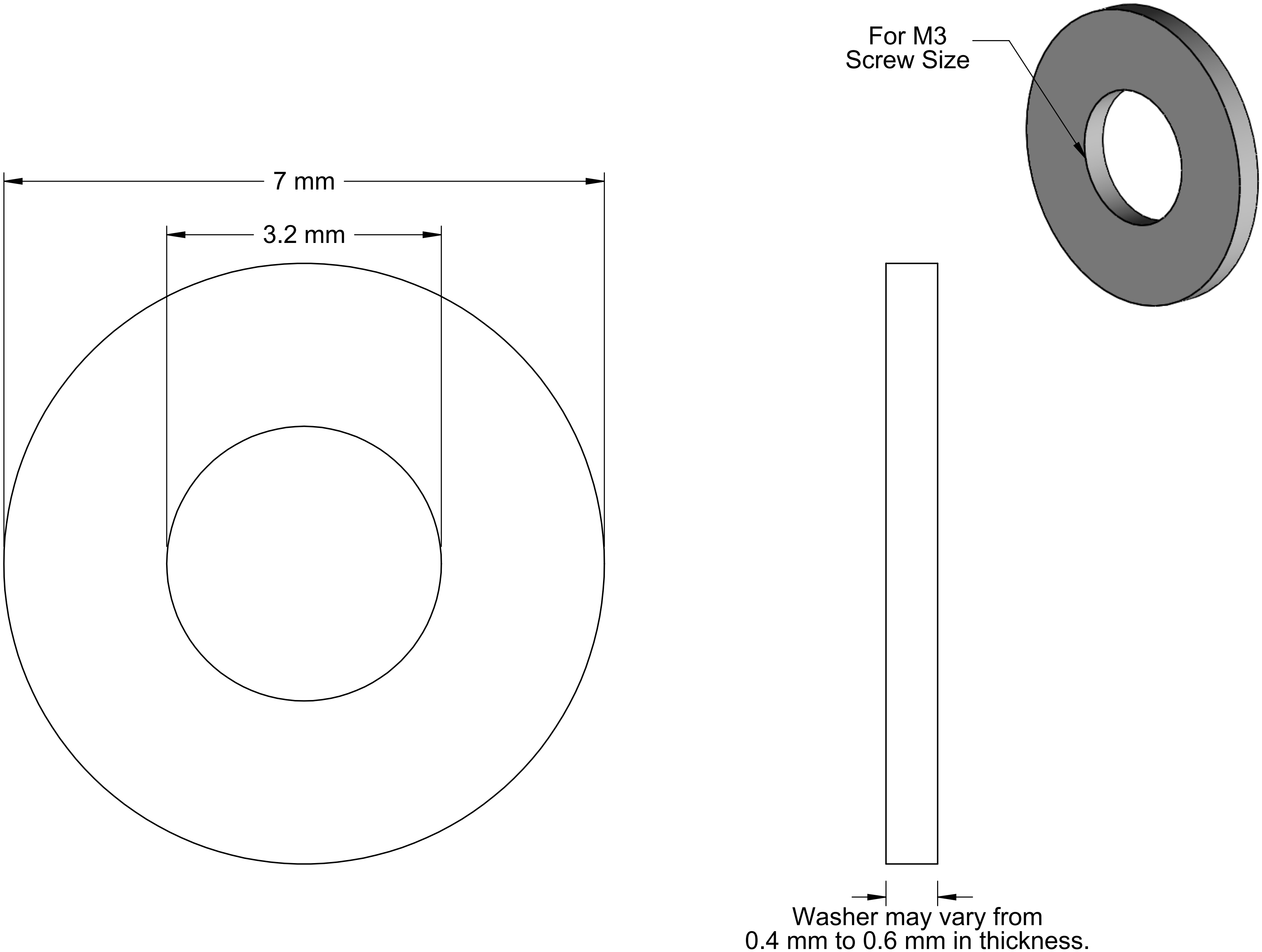


McMASTER-CARR® CAD

PART NUMBER **92949A265**

http://www.mcmaster.com

Stainless Steel Button-Head Socket Cap Screw

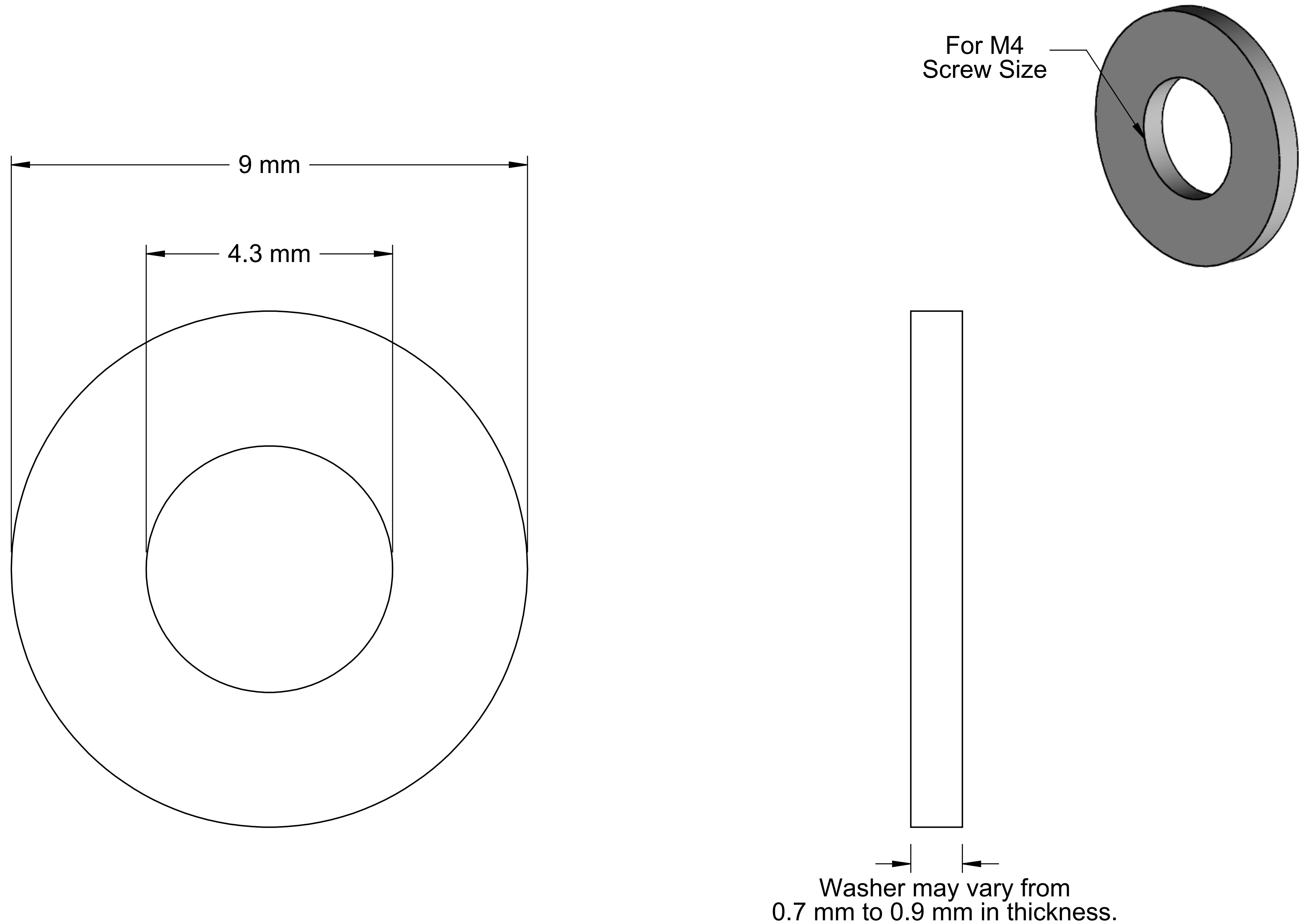


McMASTER-CARR®

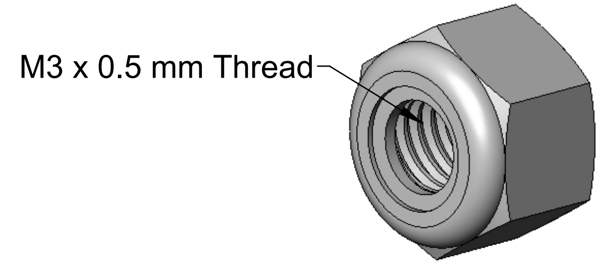
PART NUMBER **93475A210**

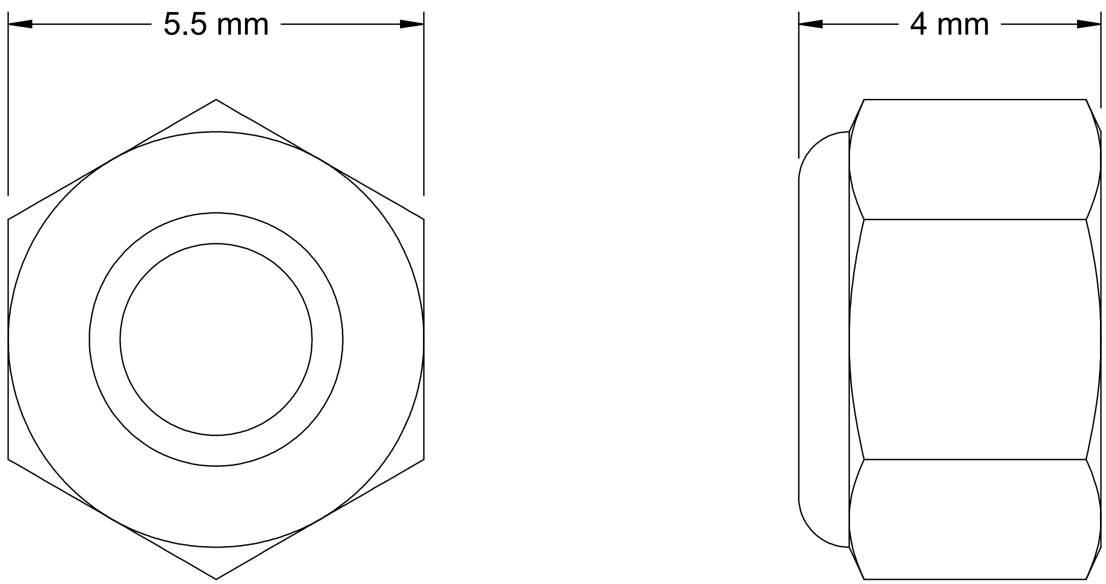
http://www.mcmaster.com

Metric General Purpose Washer



McMASTER-CARR® CAD	PART NUMBER	93475A230
http://www.mcmaster.com © 2014 McMaster-Carr Supply Company	Metric General Purpose Washer	
Information in this drawing is provided for reference only.		





McMASTER-CARR® CAD

PART NUMBER 93625A100

Metric Nylon-Insert Locknut

Appendix E. Detailed Supporting Analysis

Torque Requirement Spreadsheet Example

Global Variables		
Density Water	1000	kg/m^3
Flap Length	0.3	m
Flap Width	0.4	m
Mass ROV	10	kg
Motion Goals		
Max Velocity	0.1	m/s
Sine wave propogation (Hz)	1.00	
Lateral Drag Rover		
Cd (eliptical head)	0.3	
Area_f (front cross-section)	0.04	m^2
Flap Drag (propulsion)		
Cd (perpendicular flat plate)	2	
Area flap	0.24	m^2
Angle of Attack	0.8	radians
Force required by flap	1.41491794	N

The torque required for the wing actuation begins by finding the lateral drag of the ROV. Based on assumptions of the shape and size of the flap, we found the various coefficients of drag.

Bernoulli's Equation			
Resulting Forces from fluid Velocity Change			
Sinisuoidal Integral	3.68067		
Ry	4.416804		
Force per control surface	2.208402	Note: Two control surfaces	

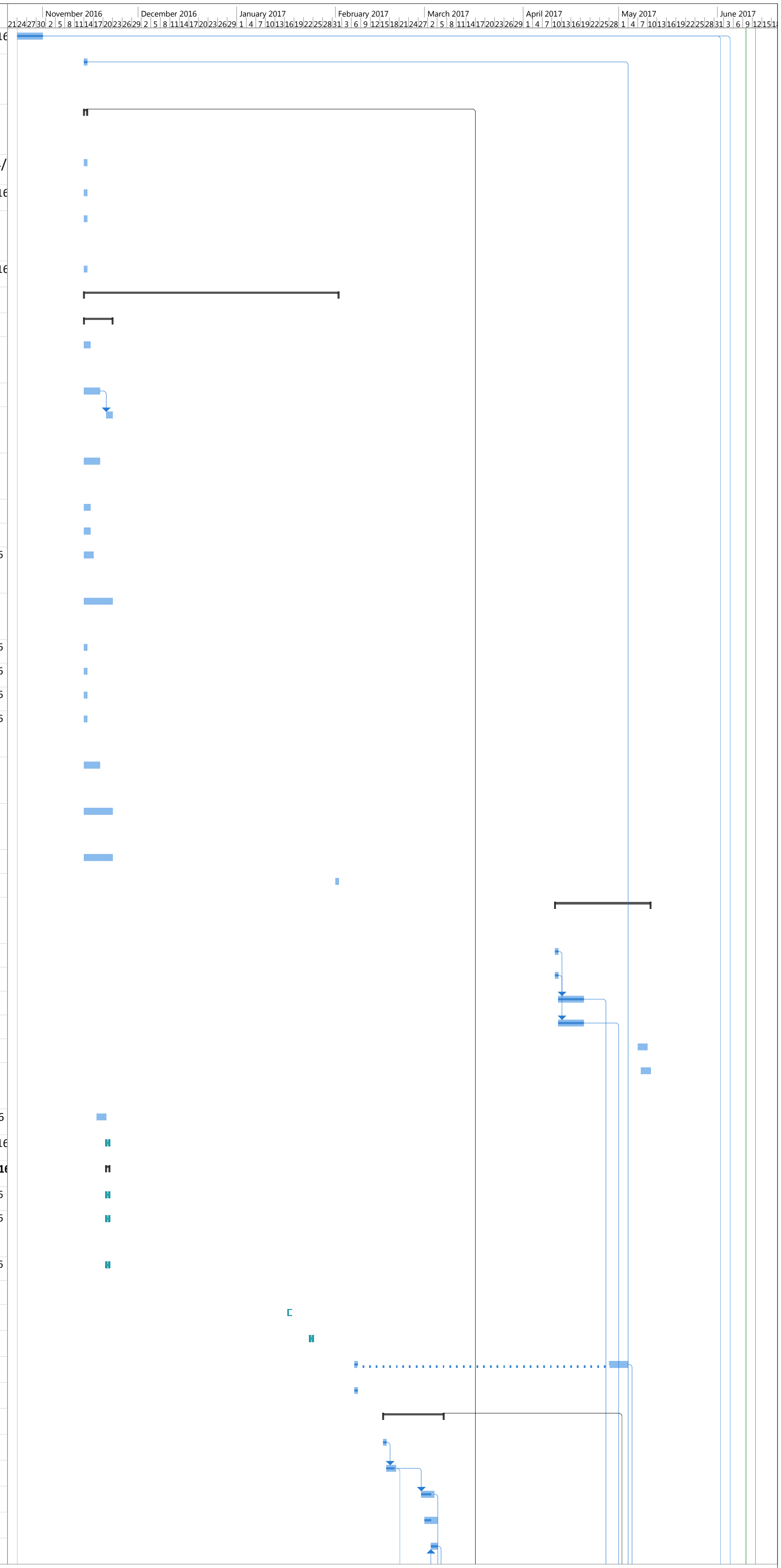
Based on Bernoulli’s Equation, the resulting forces based on the

Required force per flap	2.2	N	
Force centroid on wing (width direction)	0.67	#	
Wing lever external	0.1	m	from wing tip to pivot joint
Wing lever internal	0.05	m	from wing pivot joint to crank connecting lever
Torque Amplification (Wing Lever)	1.34	#	Length external (lever divided by internal lever) assuming force on wing acts 2/3 of the way up the lever external
** Assuming torque amplification between wing lever and crank wheels are negligible			
Required Torque	0.197516	N-m	

The torque amplification was found by multiplying the force centroid on the wing by the wing lever external and then dividing the product by dividing the wing lever internal.

Appendix F. Ocean Locomotion Gantt Chart

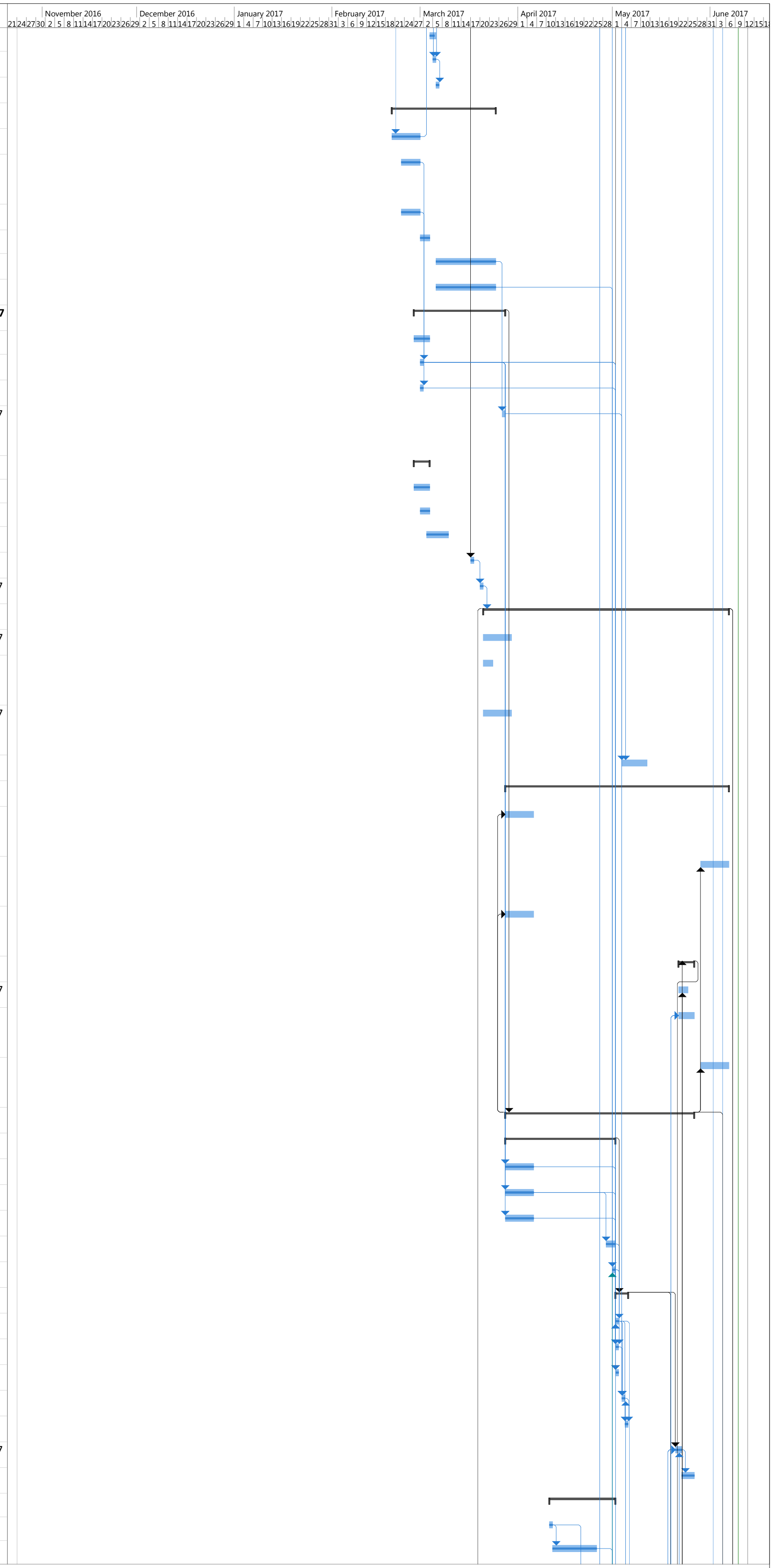
ID	Task Mode	Task Name	Duration	Start	Finish
64		Perform prototype tests	6 days?	Mon 10/24/16	Mon 10/31/16
3		Create presentation of manufacturing status and test plan	1 day	Mon 11/14/16	Mon 11/14/16
25		**Create presentation of manufacturing status and test plan**	**1 day?**	**Mon 11/14/16**	**Mon 11/14/16**
26		Critical Design Safety Review	1 day?	Mon 11/14/	Mon 11/14/
35		Create layout of final design	1 day?	Mon 11/14/16	Mon 11/14/16
36		Research performance of available components	1 day?	Mon 11/14/16	Mon 11/14/16
63		Acquire necessary testing equipment	1 day?	Mon 11/14/16	Mon 11/14/16
71		**Update necessary sections from PDR**	**58 days**	**Mon 11/14/16**	**Wed 2/1/17**
72		**Solid Model/ Layout Description**	**7 days**	**Mon 11/14/16**	**Tue 11/22/16**
73		Detailed description of functions/ components	2 days	Mon 11/14/16	Tue 11/15/16
75		Make detailed solid model	5 days	Mon 11/14/16	Fri 11/18/16
74		Make annotated layout drawing of solid model	2 days	Mon 11/21/16	Tue 11/22/16
76		Formalize Safety Hazard Checklist of final design	5 days	Mon 11/14/16	Fri 11/18/16
77		Write description of final design	2 days	Mon 11/14/16	Tue 11/15/16
78		Write discussion of final design selection	2 days	Mon 11/14/16	Tue 11/15/16
79		Explanation and justification of material selection	3 days	Mon 11/14/16	Wed 11/16/16
80		Develop fabrication and assembly instructions	7 days	Mon 11/14/16	Tue 11/22/16
81		Detailed safety considerations	1 day	Mon 11/14/16	Mon 11/14/16
82		Create final Bill of Materials	1 day	Mon 11/14/16	Mon 11/14/16
84		Create Operators Manual	1 day	Mon 11/14/16	Mon 11/14/16
85		Write Design Verification Plan, listing necessary equipment	1 day	Mon 11/14/16	Mon 11/14/16
86		Write up supporting preliminary analysis results	5 days	Mon 11/14/16	Fri 11/18/16
87		Compile vendor supplied Component Specifications and Data Sheets	7 days	Mon 11/14/16	Tue 11/22/16
88		Compile list of vendors for components	7 days	Mon 11/14/16	Tue 11/22/16
83		Update Gantt chart	1 day	Wed 2/1/17	Wed 2/1/17
123		**Ordering parts for 2nd Locomotion assembly**	**23 days?**	**Tue 4/11/17**	**Wed 5/10/17**
124		Order 2 more Pololu motors	1 day	Tue 4/11/17	Tue 4/11/17
125		McMaster hardware order	1 day	Tue 4/11/17	Tue 4/11/17
126		Receive McMaster order	6 days	Wed 4/12/17	Wed 4/19/17
127		Receive motors	6 days	Wed 4/12/17	Wed 4/19/17
129		Transmission Housing redesign	3 days?	Sun 5/7/17	Tue 5/9/17
128		Boost Converter Further Research and Planning	3 days?	Mon 5/8/17	Wed 5/10/17
41		Circuitry Analysis	1 day?	Fri 11/18/16	Sun 11/20/16
65		Work on CDR	1 day	Mon 11/21/16	Mon 11/21/16
66		**Budget**	**1 day**	**Mon 11/21/16**	**Mon 11/21/16**
67		Create Budget Spreadsheet	1 day	Mon 11/21/16	Mon 11/21/16
68		Learn about CPConnect Reimbursement Process	1 day	Mon 11/21/16	Mon 11/21/16
69		Forecast Spending and Allocation	1 day	Mon 11/21/16	Mon 11/21/16
70		Complete Reimbursement forms			
37		Decide on propulsion method		Tue 1/17/17	
62		Create testing plan and procedures	1 day	Tue 1/24/17	Tue 1/24/17
28		CDR Presentation to class	5 days?	Tue 2/7/17	Wed 5/3/17
89		Turn in CDR report	1 day?	Tue 2/7/17	Tue 2/7/17
97		**Rocker Crank Verification**	**16 days?**	**Thu 2/16/17**	**Mon 3/6/17**
98		3D print crankshaft proof of concept	1 day?	Thu 2/16/17	Thu 2/16/17
105		Test rocker crank for binding	2 days?	Fri 2/17/17	Sun 2/19/17
102		Reprint better crankshaft	4 days?	Tue 2/28/17	Fri 3/3/17
99		Test crank being motorized	4 days?	Wed 3/1/17	Sat 3/4/17
104		Create latex fin	2 days	Fri 3/3/17	Sat 3/4/17



Project: Ocean Locomotion Gan
Date: Sat 6/10/17

Task	Project Summary	Manual Task	Start-only	Deadline	
Split	Inactive Task	Duration-only	Finish-only	Progress	
Milestone	Inactive Milestone	Manual Summary Rollup	External Tasks	Manual Progress	
Summary	Inactive Summary	Manual Summary	External Milestone		

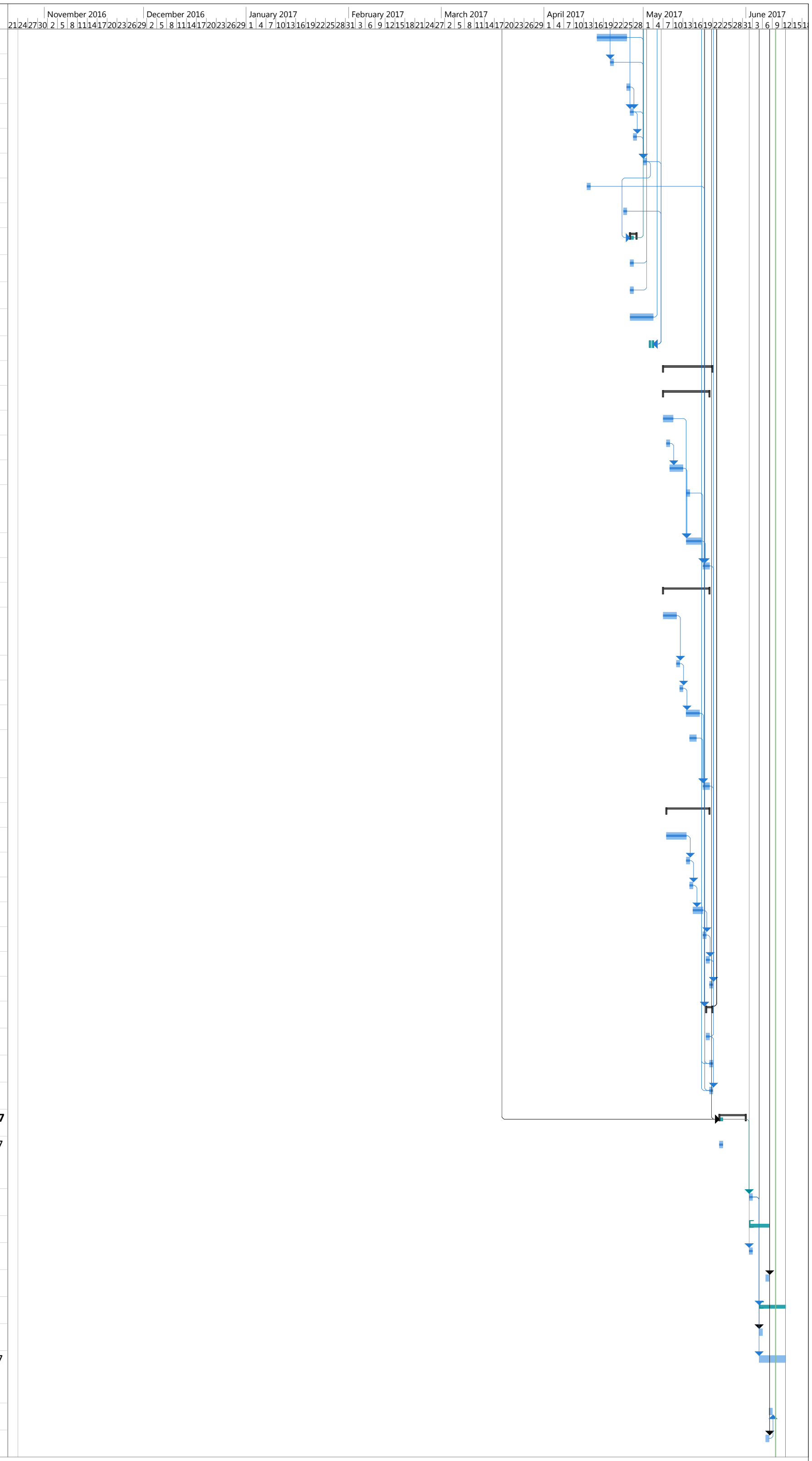
ID	Task Mode	Task Name	Duration	Start	Finish
103		Attach Latex Fin	2 days?	Sat 3/4/17	Sun 3/5/17
101		Test full fin design in air	1 day?	Sun 3/5/17	Sun 3/5/17
100		Test full fin design in water	1 day?	Mon 3/6/17	Mon 3/6/17
90		**Ordering Parts**	**27 days?**	**Mon 2/20/17**	**Fri 3/24/17**
91		Order Latex	7 days	Mon 2/20/17	Tue 2/28/17
93		Order McMaster components (Order #1)	4 days	Thu 2/23/17	Tue 2/28/17
96		Order motor from Pololu	4 days	Thu 2/23/17	Tue 2/28/17
94		Order McMaster components (Order #2)	3 days?	Wed 3/1/17	Fri 3/3/17
92		Order Waterproof electronics housing	15 days	Mon 3/6/17	Fri 3/24/17
95		Order HDPE	15 days?	Mon 3/6/17	Fri 3/24/17
57		**Receiving shipments**	**23 days?**	**Mon 2/27/17**	**Mon 3/27/17**
59		Receive latex	5 days?	Mon 2/27/17	Fri 3/3/17
60		Receive McMaster Order	1 day?	Wed 3/1/17	Wed 3/1/17
61		Receive motors	1 day?	Wed 3/1/17	Wed 3/1/17
58		Receive Waterproof electronics housing	1 day?	Mon 3/27/17	Mon 3/27/17
109		**Wait for Orders**	**5 days?**	**Mon 2/27/17**	**Fri 3/3/17**
110		Wait for Latex	5 days?	Mon 2/27/17	Fri 3/3/17
111		Wait for McMaster Order #2	3 days?	Wed 3/1/17	Fri 3/3/17
112		3D print parts	7 days	Fri 3/3/17	Thu 3/9/17
27		Project Update to Class	1 day	Fri 3/17/17	Fri 3/17/17
8		Project update to sponsor	1 day	Mon 3/20/17	Mon 3/20/17
12		**Work on FDR Report**	**60 days**	**Tue 3/21/17**	**Tue 6/6/17**
19		Write cost-analysis of design	7 days	Tue 3/21/17	Wed 3/29/17
20		Description of material, geometry and components	3 days	Tue 3/21/17	Thu 3/23/17
23		Write up safety, maintanence and repair considerations	7 days	Tue 3/21/17	Wed 3/29/17
24		Update relevant sections of CDR	7 days	Thu 5/4/17	Thu 5/11/17
16		**Manufacturing Analysis**	**55 days**	**Tue 3/28/17**	**Tue 6/6/17**
17		Record descriptions of manufacturing	7 days	Tue 3/28/17	Wed 4/5/17
18		Write recommendations for future manufacturing	7 days	Mon 5/29/17	Tue 6/6/17
21		Compile diagrams of code, wiring, schematics flowcharts	7 days	Tue 3/28/17	Wed 4/5/17
13		**Analysis of Testing**	**5 days**	**Mon 5/22/17**	**Fri 5/26/17**
14		Formalize analysis of testing results	3 days	Mon 5/22/17	Wed 5/24/17
15		Record test data and take photos of testing	5 days	Mon 5/22/17	Fri 5/26/17
22		Description of differences between product vs plan	7 days	Mon 5/29/17	Tue 6/6/17
42		**Prototype Construction**	**48 days?**	**Tue 3/28/17**	**Fri 5/26/17**
43		**Machining Operations**	**25 days?**	**Tue 3/28/17**	**Mon 5/1/17**
45		Machine motor holder	7 days	Tue 3/28/17	Wed 4/5/17
46		Machine motor housing bottom	7 days	Tue 3/28/17	Wed 4/5/17
47		Machine motor housing top	7 days	Tue 3/28/17	Wed 4/5/17
48		Machine O-ring on motor housing	1 day?	Sat 4/29/17	Mon 5/1/17
44		Machine acyrlic for chassis	1 day	Mon 5/1/17	Mon 5/1/17
49		**Assemblies**	**4 days?**	**Tue 5/2/17**	**Fri 5/5/17**
51		Chassis Assembly	1 day?	Tue 5/2/17	Tue 5/2/17
53		Motor Assembly	1 day	Tue 5/2/17	Tue 5/2/17
54		Crankshaft Assembly	1 day	Tue 5/2/17	Tue 5/2/17
50		Connect circuitry	1 day?	Thu 5/4/17	Thu 5/4/17
52		Connect MFC	1 day?	Fri 5/5/17	Fri 5/5/17
55		Test basic operation	2 days	Sun 5/21/17	Mon 5/22/17
56		Troubleshoot prototype	4 days	Tue 5/23/17	Fri 5/26/17
114		**2nd Locomotion Assembly**	**15 days**	**Tue 4/11/17**	**Mon 5/1/17**
115		Edit motor housing design	1 day	Tue 4/11/17	Tue 4/11/17
117		Machine 2 motor housing	10 days	Wed 4/12/17	Tue 4/25/17



Project: Ocean Locomotion Gan
Date: Sat 6/10/17

Task		Project Summary		Manual Task		Start-only	Deadline
Split		Inactive Task		Duration-only		Finish-only	Progress
Milestone		Inactive Milestone		Manual Summary Rollup		External Tasks	Manual Progress
Summary		Inactive Summary		Manual Summary		External Milestone	

ID	Task Mode	Task Name	Duration	Start	Finish
116		3D print 2nd crankshaft housing	7 days	Mon 4/17/17	Tue 4/25/17
118		Make O-rings	1 day	Fri 4/21/17	Fri 4/21/17
119		Make 2nd fin	1 day	Wed 4/26/17	Wed 4/26/17
120		2nd crankshaft assembly	1 day	Thu 4/27/17	Thu 4/27/17
121		Attach 2nd fin	1 day	Fri 4/28/17	Fri 4/28/17
122		Transmission assembly	1 day	Mon 5/1/17	Mon 5/1/17
113		Cal Poly Pier Safety Certification	1 day	Fri 4/14/17	Fri 4/14/17
107		Update FMEA	1 day	Tue 4/25/17	Tue 4/25/17
38		**Develop chassis design**	**2 days**	**Thu 4/27/17**	**Fri 4/28/17**
39		Determine size envelope	1 day	Thu 4/27/17	Thu 4/27/17
40		Identify material choice	1 day	Thu 4/27/17	Thu 4/27/17
108		Finalize circuitry design	5 days	Thu 4/27/17	Wed 5/3/17
106		Hardware Demo	1 day	Wed 5/3/17	Wed 5/3/17
130		**Design Revision**	**14 days?**	**Sun 5/7/17**	**Sun 5/21/17**
139		**Transmission Redesign**	**13 days?**	**Sun 5/7/17**	**Sat 5/20/17**
145		Design new transmission housing	3 days?	Sun 5/7/17	Tue 5/9/17
144		Order Delrin	1 day?	Mon 5/8/17	Mon 5/8/17
143		Wait for delrin	4 days	Tue 5/9/17	Fri 5/12/17
141		Laser Cutting cranks, rockers, crank discs	1 day?	Sun 5/14/17	Sun 5/14/17
142		Machine new housing pair	4.5 days	Sun 5/14/17	Thu 5/18/17
140		Transmission assembly	2 days?	Fri 5/19/17	Sat 5/20/17
146		**Electronics Redesign**	**13 days?**	**Sun 5/7/17**	**Sat 5/20/17**
152		Boost Converter further research and planning	4 days	Sun 5/7/17	Wed 5/10/17
151		Capacitor sizing	1 day	Thu 5/11/17	Thu 5/11/17
150		Capacitor and Polycase order	1 day	Fri 5/12/17	Fri 5/12/17
149		Wait for electronics order	4 days	Sun 5/14/17	Wed 5/17/17
148		Make new power supply (1) and MFC leads (2)	2 days?	Mon 5/15/17	Tue 5/16/17
147		Electronics Assembly	2 days	Fri 5/19/17	Sat 5/20/17
132		**Exo-Shell Design**	**12 days?**	**Mon 5/8/17**	**Sat 5/20/17**
138		Design Shell	5 days?	Mon 5/8/17	Sat 5/13/17
137		Mold build	1 day?	Sun 5/14/17	Sun 5/14/17
136		Shell lay-up	1 day?	Mon 5/15/17	Mon 5/15/17
135		Shell cure	3 days	Tue 5/16/17	Thu 5/18/17
134		Clean up machining	1 day?	Fri 5/19/17	Fri 5/19/17
133		Paint shell	1 day?	Sat 5/20/17	Sat 5/20/17
131		Full prototype assembly	1 day?	Sun 5/21/17	Sun 5/21/17
4		**Testing**	**2 days?**	**Sat 5/20/17**	**Sun 5/21/17**
7		Schedule time at CP Pier	1 day?	Sat 5/20/17	Sat 5/20/17
5		Test 2 (Specification 4)	1 day?	Sun 5/21/17	Sun 5/21/17
6		Test 1 (Specifications 1,2,5)	1 day?	Sun 5/21/17	Sun 5/21/17
33		**Prepare Expo poster**	**6 days**	**Wed 5/24/17**	**Wed 5/31/17**
34		Write functional description of final design	1 day?	Wed 5/24/17	Wed 5/24/17
1		Project Expo	1 day?	Fri 6/2/17	Fri 6/2/17
9		**Turn in deliverables to Dr. Kitts**		**Fri 6/2/17**	
11		Give ROV to Dr. Kitts	1 day?	Fri 6/2/17	Fri 6/2/17
10		Hand in FDR to sponsor	1 day?	Wed 6/7/17	Wed 6/7/17
29		**Post Expo tasks**		**Mon 6/5/17**	
30		Clean up work/ storage areas	1 day?	Mon 6/5/17	Mon 6/5/17
32		Complete remaining tasks from Senior Project Completion Checklist	6 days	Mon 6/5/17	Mon 6/12/17
31		Upload FDR to digital commons	1 day?	Thu 6/8/17	Thu 6/8/17
2		FDR Report Turn In	1 day?	Wed 6/7/17	Wed 6/7/17



Project: Ocean Locomotion Gan
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Task		Project Summary		Manual Task		Start-only		Deadline	
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Summary		Inactive Summary		Manual Summary		External Milestone			

Appendix G: Marine Gastrobot Operator's Manual

The following Operator's Manual summarizes the steps to safely operate the Marine Gastrobot, a small ROV utilizing an MFC to power fin actuators for forward locomotion. This manual will include checks of critical seals and components, adjusting the parameters the ROV will operate in through buoyancy control, and preparing the ROV for operation. This manual is divided into the following sections:

1) Electronics
2) Hardware
3) MFC
4) Buoyancy Trimming

1. Electronics

The electronics for the marine gastrobot function to boost power generated by the microbial fuel cells (MFCs) and distribute that energy to motors used for locomotion. The following steps outline the procedure for wiring the electronics on the gastrobot.

1) Connect the leads from the capacitor to the screw terminal block labeled "BAT_SEC" and "GND" (Figure 1 below). Ensure that the positive (red) lead from the capacitor matches with the "BAT_SEC" terminal and the ground (black) lead goes to "GND". Ensure that the ground lead is attached to the negative pin of the capacitor. This will often be marked with a "-" on the side of the capacitor as shown in Figure 1.

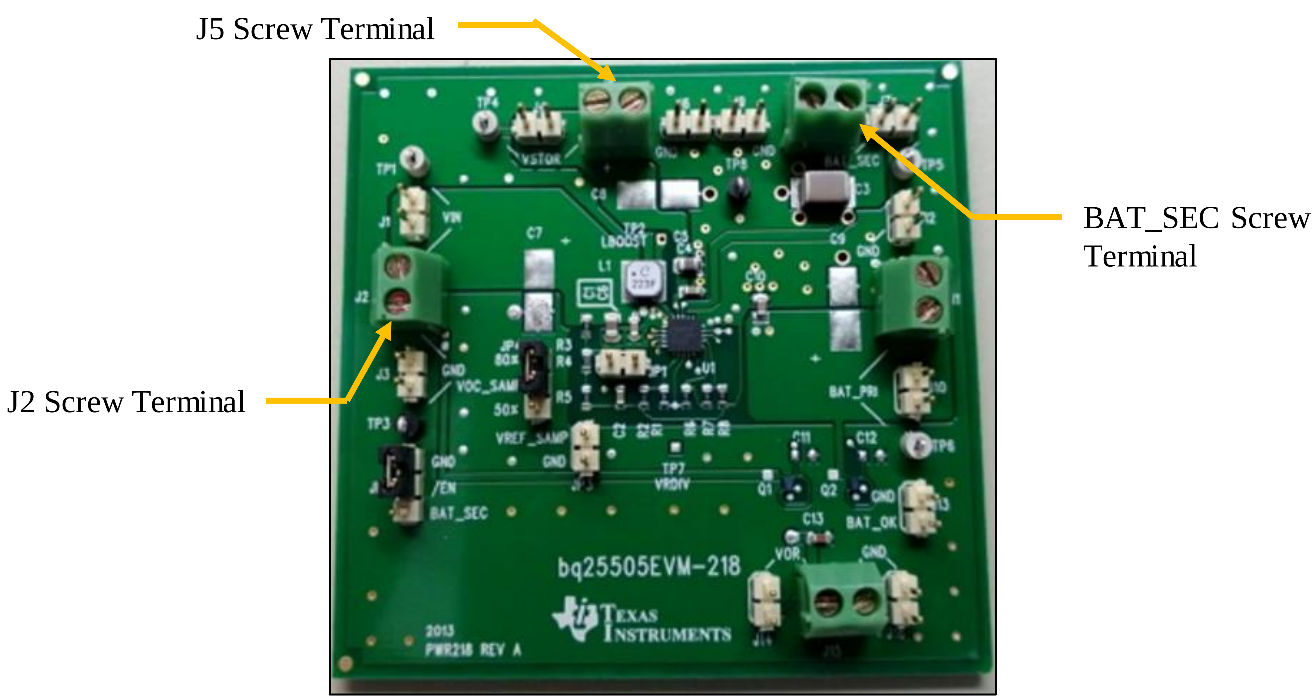

Figure 1. Top View of TI BQ25505 EVM Board Boost Converter.

2) Connect the leads from the motor to the screw terminal labeled J5. To get the gastrobot to move in the forward direction, connect the positive (red) lead to “VSTOR” and the ground (black) lead to “GND”. To reverse direction, reverse these connections.
3) Connect the leads from the MFC array to the screw terminal labeled J2. Ensure the positive (red) lead is connected to “VIN” and the ground (black) lead is connected to “GND”.

2. Hardware

The critical hardware of the Marine Gastrobot is the motor housing and the locomotion rocker-crank shaft assembly. Before operating the ROV, it is essential to perform checks on the hardware to ensure safe usage.

2.1 Motor Housing Safety Checks

1) Remove bolts securing motor housing to chassis
2) Remove motor housing and inspect for visible damage (i.e. cracks)
3) Open the motor housing
4) Inspect O-ring for visible damage (i.e. cracks, separation)
5) Remove motor and motor mount
6) Replace motor shaft with dowel pin in shaft seal
7) Place paper towels in motor housing
8) Reseal motor housing
9) Submerge motor housing completely for 10 minutes
10) Remove motor housing from tank
11) Open motor housing
12) Check paper towel for dampness
13) If paper towel is wet, replace O-ring. Otherwise reassemble motor and motor mount in motor housing and reseal
14) Reattach motor housing to chassis

2.2 Rocker-Crank Shaft Safety Check

1) Remove coupler to the motor shaft
2) Spin input shaft by hand to check for binding or rockers failing to move
3) If any failure, open locomotion housing
4) Check for shaft disconnections or extreme shaft misalignment
5) Tighten shoulder bolts and check pins
6) Reassemble the assembly and couple to the motor

3. MFC

Proper MFC maintenance is deferred to the MFC team.

4. Buoyancy Trimming (2 persons required)

- Locate the four weight trimming pockets on the underside of the four corners of the MFC Rover chassis.
- Collect the buoyancy trimming weights and a ~10 foot long piece of polymer rope
- Locate and tie the polymer rope to the central hook on the top of the rover (this will act as a tether during the buoyancy trimming process).

CAUTION: Snorkel gear will be required at this point to make visual inspections of the buoyancy trimming process.

- Open the Velcro™ pockets and submerge the fully assembled rover into the water. Ensure that someone is holding onto the tethering line while the rover is being submerged.
- Lower the MFC Rover until the 3ft operation depth. Add weights to the rover evenly across the four corners if it is not sinking.
- Once at 3ft begin removing weights while releasing tension on the tethering line after each additional weight to check for neutral buoyancy (Note: during this time the craft may pitch, roll, or yaw. Ensure that you are adding weights evenly or focusing weights on specific corners to prevent any attitude change other than a parallel orientation with the surface of the water).
- Continue operation until the tether is no longer required and the rover remains neutral buoyant and parallel at the operational depth of 3 feet.

5. Syncing Transmissions

1) Remove motor housing lids for easier access to the motor leads
2) Disconnect the bullet connectors for the motor with the transmission to be synchronized to
3) Turn on power supply to engage the fin movement
4) Watch the leading edge of the fin and turn off the power supply when the active fin is in approximately the same position as the stationary fin
5) Connect the other inactive motor's bullet connectors
6) Turn on the power supply and test the synchronization of the fins

6. Safely Discharging the Capacitor

After operation of the ROV, it is important to fully discharge the capacitor for safe transportation and storage

1) Dry off the ROV as best as possibly with rags or towels
2) Dry hands and put on rubber gloves and safety glasses as a precaution
3) Remove top of electronics housing
4) Disconnect capacitor from leads
5) Connect a resistor of approximately 10Ω with a 10W rating to the leads of the capacitor
   CAUTION: If the resistor feels warm, disconnect the resistor, and allow to cool. If the resistor feels hot, it is recommended that you find a resistor with a higher resistance and power rating
6) Periodically use a volt meter to check the voltage across the capacitor. A capacitor is safely discharged when the voltage reaches approximately 0V, or less than 0.01V

Appendix H. Bill of Materials

Part Number	Component	Quantity
1000	**Marine Gastrobot**	
2000	**Chassis Assembly**	**1**
3000	Chassis Base	1
3001	Chassis Retainer	1
3002	Chassis Top	1
2001	**Transmission Housing Assembly**	**2**
3003	Modular Housing	3
3004	Modular Endcap	1
3005	Sleeve Bearing	4
3006	Threaded Insert	3
3007	Shoulder Bolt	3
3008	Alignment Pin	6
3009	Through Bolt Rod	4
3010	Through Bolt Nut	6
3035	Connecting Shaft	2
3036	Drive Shaft	1
3037	End Shaft	1
2002	**Drive Train Assembly**	**2**
3011	Crank Disc	2
3012	Crank Pin	1
3013	Coupler	1
3014	Coupler Pin	1
3015	Rocker	1
3016	Latex	1

Part Number	Component	Quantity
2003	**Motor Housing Assembly**	**2**
3017	Motor Housing Bottom	1
3018	Motor Housing Top	1
3019	Motor	1
3020	Motor Mount	1
3021	4mm Shaft Coupler Hub	1
3022	Spider	1
3023	1/4in Shaft Coupler Hub	1
3024	O-Ring	1
3025	Wire Pass Through Connector	1
3026	Sleeve Bearing	1
3027	Dynamic Shaft Seal	1
3028	M3x0.5mm x 4mm Length SHCS	2
3029	5-40 x 0.25in Length BHCS	4
3030	1/4-20 x 1in Length SHCS	4
2004	**Electronics Assembly**	**1**
3031	EVM Board	1
3032	Capacitor	1
3033	PolyCase	1
3034	Wire Gland	2