Team 24 Final Report

Non-Propeller Propulsion System for a Human Powered Submarine

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Background

The International Submarine Races (ISR) is a competition in which teams race “wet” submarines. A “wet” submarine is an internally flooded, fully enclosed, vehicle in which the pilot(s) must breathe from a SCUBA apparatus [1]. The racecourse is a 100 yard straight sprint. The submarines compete in four categories: 1 and 2 person propeller, and 1 and 2 person non-propeller. A propeller system is defined as a water-coupled device with radiating blades that create thrust when spinning. A non-propeller system is defined as any other water-coupled device that creates a thrust when operated. A bottom crawling vehicle is not a water-coupled device [1]. The University of Michigan Human Powered Submarine Team (HPS) traditionally builds single person propeller driven submarines [1].

The Problem

HPS wants us to develop and create a non-propeller propulsion module that can take the place of the current propeller module in order to compete at the International Submarine Races in the -non-propeller category. The new, non-propeller propulsion system must be able to be easily switched with the current propulsion system without affecting the rest of the submarine.

Benchmarks

Submarines predominantly use propellers, even the standard screw propeller can produce high efficiency on the order of 80 percent. [2] However, jet propulsion is also used where water is drawn in and thrust out near the stern. This leads to no moving parts outside the main hull, so jet propulsion tends to be used in shallow water applications. Since an impeller is used to pump the water, the overall efficiency is less than that of a propeller system because of friction loss from the inner wall ducts. [3] Propellers and jet propulsion are the two main systems in use by submarines today. Magnetohydrodynamic (MHD) systems are being researched but are not in commercial use. One of the main problems is the relative efficiency compared to other forms of propulsion. The efficiency of a MHD system is proportional to the magnetic flux intensity, so very powerful magnets are needed. [4] To find other comparable models to what we are trying to achieve, other submarines in the human powered submarine competition and other underwater systems need to also be studied.

Many different teams have already attempted to create an efficient non-propeller propulsion system for the International Submarine Races. Some teams were very successful while others did not perform as favorably. The team from Ecole de Technologie Superieure in Montreal, Quebec, Canada, was successful in developing a propulsion system using oscillating, lateral wings on either side of the hull. The wings are powered by a bicycle pedaling system which converts rotational energy into an oscillating motion. The wings on this submarine, called *Omer 6*, are in the shape of an airfoil, where the fluid displacement around each wing creates a lift force. The design allows for the wings to oscillate upwards and downwards, creating a lift force in both directions. The angle of the wings can also be adjusted to account for the arrival of fluid at each speed. The wings also experience a drag force from the resistance of the fluid. Together, these forces propel the submarine forward [5]. *Omer 6* performed very successfully at the 10th ISR and currently holds the non-propeller submarine top speed record of 4.916 knots [6].

The team from UC San Diego created a non-propeller submarine, *Odin's Rage*, which also performed successfully at the 10th ISR competition. *Odin's Rage*, like Omer 6, relies on a bicycle pedaling system, but moves a fish-tail and fin laterally through the water with the use of a connected set of crank arms and a piston rod [7]. *Odin's Rage* achieved a maximum speed of 4.103 knots, coming in 2nd to Omer 6 [6]. The same team developed another submarine called *Odin's Revenge* a year later. The main goal of this project was to optimize the reliability of the existing drive train introduced in *Odin's Rage* [8]. Despite their efforts, *Odin's Revenge* actually performed worse, achieving a top speed of 2.884 knots [6].

The University of Maine developed a submarine called *Lobstar I*, which relies on the existing Hobie Mirage drive system. Two Hobie Inc. manufactured Mirage Drive hydrofoils are mounted on top and bottom of the submarine. The system works by converting a stair stepping motion from the pilot into an oscillatory motion of the propulsion fins, mimicking how penguins swim through the water [9]. This submarine achieved a top speed of 3.996 knots at the 10th ISR [6].

Other methods include the use of Biomimetics to produce thrust. The approach for Biomimetics boasts enhanced performance and efficiency in underwater exploration. [8] The key principle is that marine animals produce thrust by flapping or oscillating their fins. In studying how marine animals swim, one can maximize performance underwater while minimizing energy requirements. Such methods are said to be superior to engineered methods of underwater exploration, and produce less pollution. [8]. There are two primary categories of biomimetic devices; undulating and oscillating. An undulating device always has at least one full wave present on the fin. A mantaray is an example of a fish with undulating fins. Undulating fins have been replicated in devices that use many in-line actuators [10] or complex gearboxes [11] to generate the waveform. An oscillating device never has a full waveform present in the fin. A dolphin has an oscillating tail fin. Michael Rufo designed an oscillating biomimetic fin structure that relied on a flexible spring structure with a fin at the end, which would oscillate to produce thrust [12]. Otto Laser designed a device with a fin on a swinging arm at the aft of the vessel for propelling small watercraft [13]. Outside of the main two categories are pump like mechanisms which take water in and expel them. A cuttlefish imitated impulse type water jet propulsion would fall into this "other" category of pump like devices [14].

User Requirements

The Michigan submarine team set forth that they want a non-propeller propulsion system that they can use in the non-propeller part of the competition. Thus our main goal is to make a non-propeller propulsion system. Furthermore, we were told that the system cannot affect the rest of submarine. This means that we cannot change the hull, weight, or center of gravity of the submarine; the submarine must operate the same with the new propulsion system. Also since the system will have to be switched out during the competition, it must be easy to remove and attach. The competition takes places in multiple conditions from chlorinated water to salt water, so all its parts must be corrosion resistant. Finally to comply with the competition rules, no foreign matter may be leaked into the water and any moving parts must be coated at the tips with high visibility paint.

Engineering Specifications

Table 1: User Requirements and Engineering Specifications

User Requirements	Engineering Specifications
Thrust Without Propeller	Propulsion system must create thrust without radiating blades that spin Rotation of blades < 360 degrees
Sufficient Forward Thrust	Average Speed of the Submarine > 2.52 knots
Same Mass as Existing Propeller	5%
Same Center of Gravity as Existing Propeller	5%
Easy to Switch Out	Time < 20 minutes with three people and basic tools underwater
Non-corrosive Materials	Aluminum, Stainless Steels and Plastics
Budget	$2000

From these user requirements we generated the engineering specifications given in table 1 above. First the propulsion system must not have rotating blades that spin more than 350 degrees to create thrust. This is to keep with the requirement of thrust without a propeller. Also the submarine must be able to achieve an average speed of 2.52 knots with the new, non-propeller system. 2.52 knots is the historic average of the non-propeller, one person submarines in the ISR competition [15]. To be a competitive and useful design, we decided that that we must be able to at least achieve the historic average.

The mass and center of gravity of the new propulsion system must be within 5% of the existing propeller system. This means that the overall mass and center of gravity of the submarine will be left unchanged. This will allow for the submarine team to switch to our non-propeller system without having to make any other changes to the rest of the submarine.

It must take three people no longer than 20 minutes to switch out the system underwater with basic tools. The team will have 30 minutes to make the switch at the competitions, and in order to be easy to switch out, we decided that they should have at least 10 minutes to spare.

Since the competition will take place in a variety of types of water, all the material will be made of non-corrosive materials such as aluminum, stainless steels, and plastics to name a few. The team has given us a budget of $2000.

These engineering specifications fully define the goals and constraints of this project. If these engineering specifications are followed, the Michigan submarine team will be able to compete in the non-propeller categories and be competitive with the rest of the teams with their current submarine. Furthermore, a design that can beat the historic average on its first iteration can be further improved and built upon. The main specification is to be able to compete in the non-propeller category, while the rest of specification are to follow the competition regulations and make the design competitive.

Concept Generation

Our project is simple in that there is only one main functions, to provide propulsion. Since there are not many components of our project, we focused more on generating full solutions rather than using functional decomposition. To do this, we started by generating full solutions on our own. This included trying to individually achieve concept variety and find practical ways to implement our ideas. After we started generating our concepts, we met together to share our concepts and provide input for each other. We then separated again and generated five concepts each. A brief description of each of the 20 concepts can be found in Appendix A. From these 20 concepts, we combined the concepts that were extremely similar and brought these concepts into our concept selection phase. We were able to narrow down our concepts to four concepts. These concepts are described below.

Water-jet with Rotating Case
A water-jet driven by an enclosed impeller attached to the case, such that the case would rotate with the impeller. This idea is simple since the case and impeller can be directly attached to one another and rotate together. However, having the case spin would lead to viscous losses.

Water-jet without Rotating Case
A water-jet driven by a semi-enclosed impeller. The impeller case would be stationary. Water is taken in through one end, and with the use of an impeller, accelerated and moved out the other end.

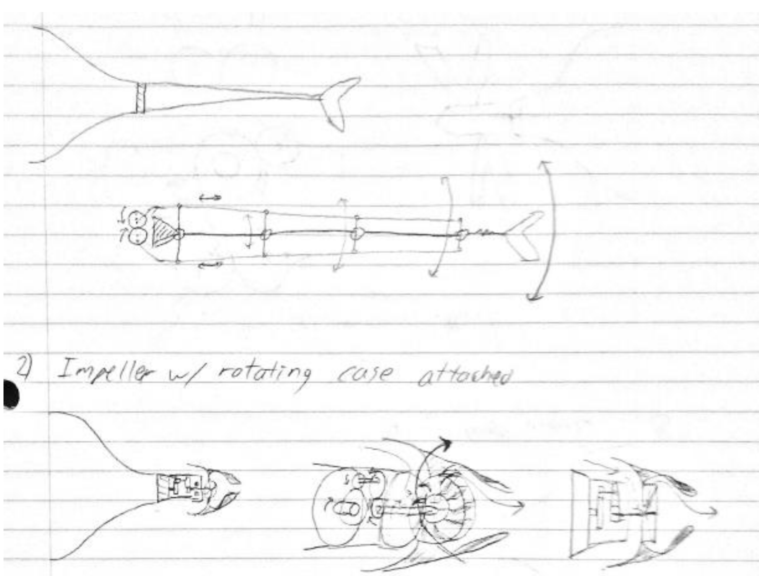


Figure 1: Water-jet/Impeller Propulsion System with and without a Rotating Case Concepts

Double Hobie Drive

A system utilizing two pairs of hobie fins. The fins would be actuated from rocker linkages. The two pairs of fins would be placed such that the net force vector would only be backwards.

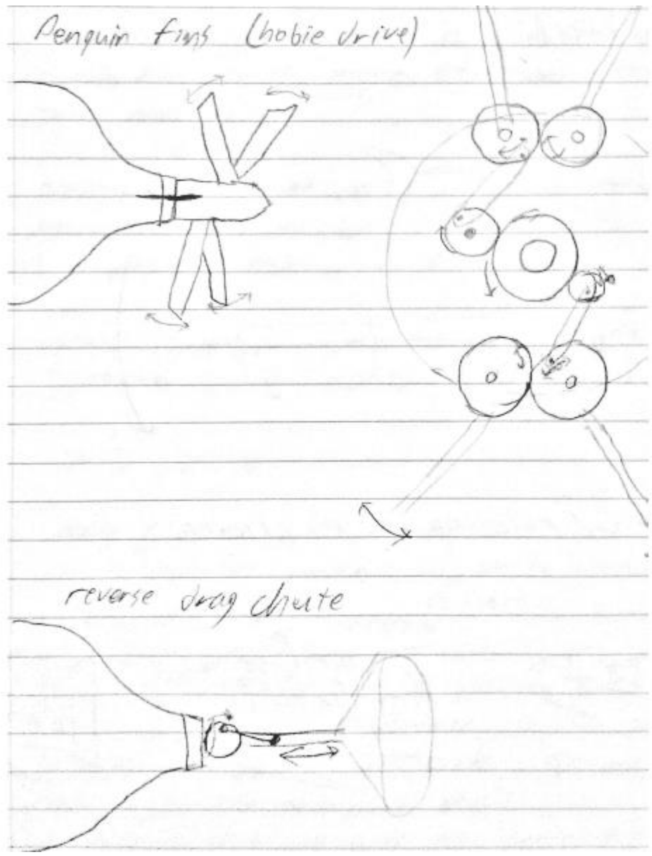


Figure 2: Double Hobie Drive Concept

Vertical Flipper

In this concept, a mono-fin is used to generate thrust. Each shaft rotates a crank-rocker linkage that will oscillate the fin, imitating how a dolphin propels itself. Unlike the first concept, this does not use a network of cables.

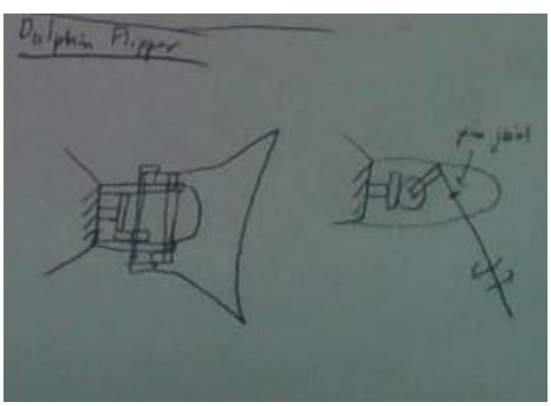


Figure 3: Vertical Flipper Concept

Concept Selection

During our concept selection phase, we evaluated each concept of propulsion methods using a Pugh Chart, and analyzed them under several criteria: Thrust efficiency, manufacturability, ease in mathematical theory, durability of design, mass and center of gravity, safety, size/drag effects and mock-up feasibility. Each criteria was ranked by importance from 1-8, with the higher number indicating the most important criteria. We then scored each of our concepts for each criteria we established from 1-5, with 5 being the best in that category. The next step was to multiply the score that each concept received for each criteria by the weight of each criteria to obtain a sub-score. Finally, we summed all of the sub-scores to obtain a total score for each concept. As a result, we were able to narrow our list of 20 concepts down to the top four options with the highest total scores. The four highest scoring concepts were an impeller with a rotating case, an impeller with a stationary case, a double Hobie drive system, and a flipper with a linkage system.

Thrust efficiency is how well the system will be able to convert the pedaling power of the human into useful thrust, translating into how fast the submarine will move. This is our most important criteria because it is the main goal and challenge of our project. So we gave this criteria the highest weight of 8.

Manufacturability is the second most important criteria with a weight of 7. We must be able to manufacture what we design. Also the easier the design is to make, the more effectively we will be able to implement the design.

Ease of mathematical theory is the next most important criteria with a weight of 6. This criteria is for how easily we will be able to do the math behind the design and as a result optimize. If we are unable to optimize the design, we might not be able to meet our engineering specifications for speed.

Durability is how well the design will deal with crashes and continues use. Since crashes with the ground or walls are somewhat common underwater, the system must not fail easily under impact. We gave this criteria a weight of 5.

Mass and center of gravity received a weight of 4. We do have to meet mass and center of gravity specifications; however since mass and center of gravity are simple to adjust, this received a relatively low score.

Safety, size/drag effects, and mock-up feasibility where our least important criteria. Safety gained a score of 3 since other team members could be around the submarine while it’s moving, and safety is always important. Size/drag effects gained a score of 2 since we don’t want our system to be unwieldy to transport or cause drag. The team will have to potentially move the part around and attach it to the submarine underwater, so we didn’t want something too big. Mock-up feasibility, received a score of 1. We want to be able to make prototypes and test the design we make.

Criteria Weight	Weight	Propeller	Weighted Subtotal	Rotating Case Waterjet	Weighted Subtotal	Stationary Case Waterjet	Weighted Subtotal	Double Hobie Drive	Weighted Total	Vertical Flipper	
Thrust Efficiency	8	5	40	3	24	3	24	3	24	3	24
Manufacturability	7	3	21	3	21	3	21	3	21	3	21
Ease of Mathematical Theory	6	2	12	4	24	4	24	3	18	3	18
Durability	5	3	15	5	25	5	25	3	15	4	20
Mass and Center of Gravity	4	4	16	4	16	4	16	4	16	2	8
Safety	3	2	6	5	15	5	15	3	9	4	12
Size/Drag Effects	2	3	6	4	8	4	8	2	4	2	4
Mock-Up Feasiblity	1	3	3	2	2	2	2	2	2	3	3
Weighted Total			119		135		135		109		110

Figure 4: Pugh chart of the top four concepts. The propeller is also in the chart as a baseline.

As can be seen from the pugh chart, the impellers scored above all the other concepts, even above the propeller which we used as a baseline. Technically, propellers are still more efficient than waterjet/impeller systems. However, taking the other factors such as ease of mathematical theory and safety into account, an impeller system is better for our specific application and resources. None of the other designs score nearly as high as the impeller concepts, so we decided to go with a stationary case impeller propulsion system. Even though the two impeller systems scored the same, we chose the one with the stationary case because we believe it will be slightly better at creating thrust. A stationary case waterjet system would not have the viscous losses of of a rotating case, and we could add fins to straighten out and improve the exit flow of a stationary impeller system.

Key Design Drivers and Challenges

The simplest competent model is a cross-sectional view of the impeller module showing how the water will flow through the ducting and impeller (Fig. 5). The cross-sectional model was chosen as the simplest competent model because it represent the idea without getting trapped in a mess of math. The mathematical model for predicting the performance of the impeller is a large, cumbersome set of equations which cannot be reduced.

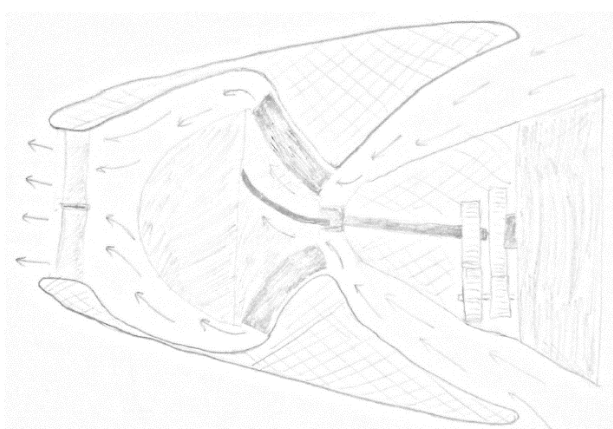


Figure 5: The cross-sectional view of the impeller shows that the water will be taken in at the right, directed through the impeller, then out the nozzle on the left.

During our project, issues we will have to deal with include working within time constraints, as well as design constraints. In addition, our key design drivers are determining a non-propeller method of propulsion, only working off of the back of the submarine, and we cannot modify the existing shafts. By far, the most challenging aspect of our design process is trying to come up with methods produce thrust without rotating blades, some of which included converting rotational motion to reciprocating motion. Due to the design constraints, our options become limited, and it becomes difficult to fabricate a module that can efficiently produce a desirable thrust. We anticipate that designing modules based on the imposed restrictions run the risk of sacrificing speed and thrust efficiency during performance. Problems that resulted depended on which concept path we choose. If we chose to use fins, we would need to buy them, as we might not have access to the material needed to construct. If we take the impeller method, we would need to use CNC milling to create the part. When it came to deciding which method was more feasible, we had to consult experts from the Naval Department. After consulting, they recommended the impeller as the most viable method of propulsion. However, the issues now lie in optimizing the impeller geometry for thrust. The mathematical analysis may not be easy, so it is now a matter of acquiring software or coding to help us optimize the impeller geometry before constructing our parts.

Mock-Up

The mock-up is a cross-sectional view of the impeller propulsion concept module. The concept module is composed of the mounting point, gearbox, impeller, impeller case, impeller duct, and nozzle.

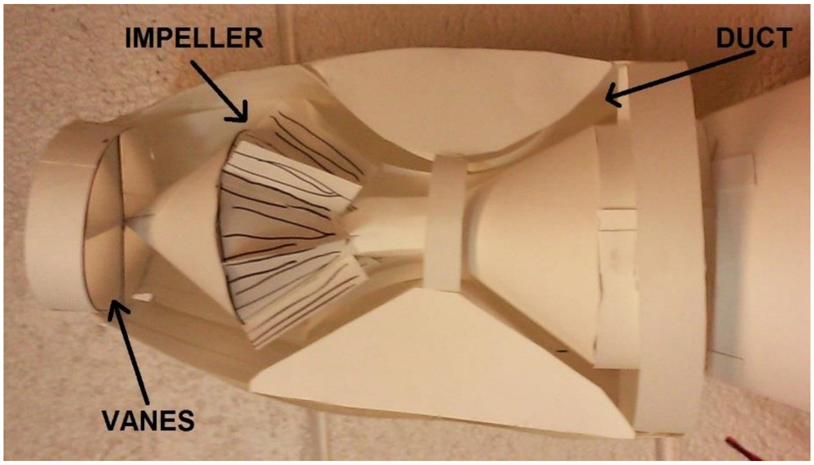
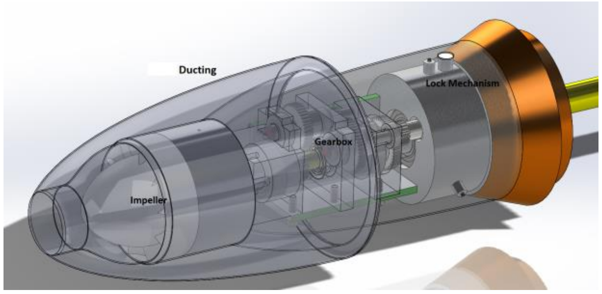


Figure 6: As shown in the Mock-up design, the primary three components are the impeller, duct, and vanes.

Concept Description

As discussed in the last design review, our team chose to implement an impeller to generate thrust in our final design. In order to successfully mount the impeller module to the existing submarine as well as efficiently generate enough thrust to propel the submarine to reach our desired speed, we had to consider four major components; the ducting, the gearbox, the mounting mechanism, and the impeller itself. Each of these components are highlighted in Figures 7a and 7b below. We will look into each of these components in more detail.



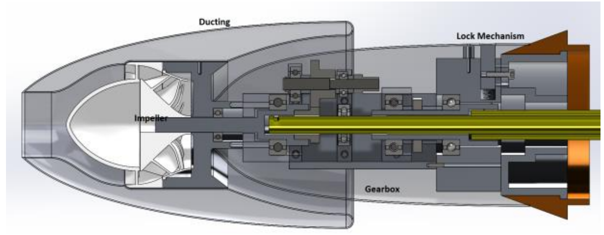


Figure 7a: CAD model of Impeller Module   Figure 7b: Cutaway view of Impeller Module

Ducting

The ducting mechanism, shown below in Figure 8, is designed to control the flow of water entering the impeller as well as directing the water that is exiting. It can be seen that the water enters the ducting mechanism all around the right side of the image, follows the casing direction into the impeller and then focuses the water exit into one, steady flow. The design process for the ducting was fairly difficult, as it is dependent on the size and shape of both the gearbox and the impeller. While we are still optimizing the dimensions of the impeller, this will change both the size of the gearbox and impeller, meaning we will have to also adjust the size and shape of the ducting mechanism. Additionally, the ducting will have to be optimized for constant acceleration. We plan to make the ducting out of fiberglass.

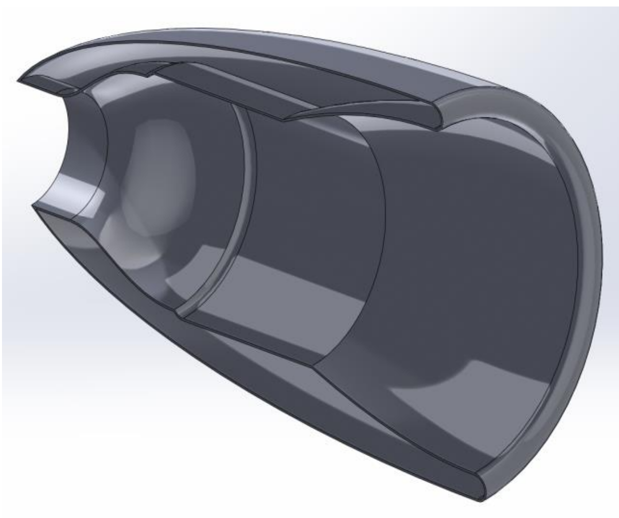


Figure 8: CAD model of Ducting Design

Gearbox

Another component of the impeller module is the gearbox, shown in figure 9 below. The current transmission is set up to gear up from the existing drive train's 220 RPM to the required 2700 RPM for the impeller. It consists of 3 stages to increase the RPM. It starts with a 54 mm pitch diameter gear that is connected to the input shaft that is then meshed to a 22.5 mm pitch diameter. This gear rotates on the same shaft as a 48 mm pitch diameter gear that meshes with a 15 mm pitch diameter gear. This gear rotates on the same shaft as another 48 mm pitch diameter gear which finally meshes with a 30 mm pitch diameter that is placed on the shaft that drives the impeller. Each of the gears came with different sized hubs that we will have to adapt to with the use of spacers. All of the shafts are connected by bearings that are placed within the front and back plate for stability and smooth, continuous rotational motion.

One initial concern in designing the gearbox was that in the original submarine, there is a 5/8th inch diameter shaft that extends about 9 inches past where this gearbox is connected to. As a result, we had to account for this shaft going through the last gear. Our solution to this was to have this 5/8th inch shaft run through the last gear without it actually being attached. Meanwhile, the shaft that connects to the impeller will be hollow and connect to the outside of the last gear so that it does not interfere with the original shaft in anyway, no longer making this extended shaft a concern in our design. All gears, spacers, shafts and bearings will be made out of stainless steels, and aluminum in order to follow the requirement of being corrosion resistant. Finally, this entire transmission component of the impeller module needed to be completely encased in order to help direct the flow of water around it and towards the impeller. This casing will be made out of fiberglass composite.

As previously mentioned, we are still in the process of optimizing the most effective dimensions and output speeds for the impeller, which means that the gear ratios are not yet finalized. Keeping this in mind, the dimensions of the casing may change in the final design after finalizing the gear ratios.

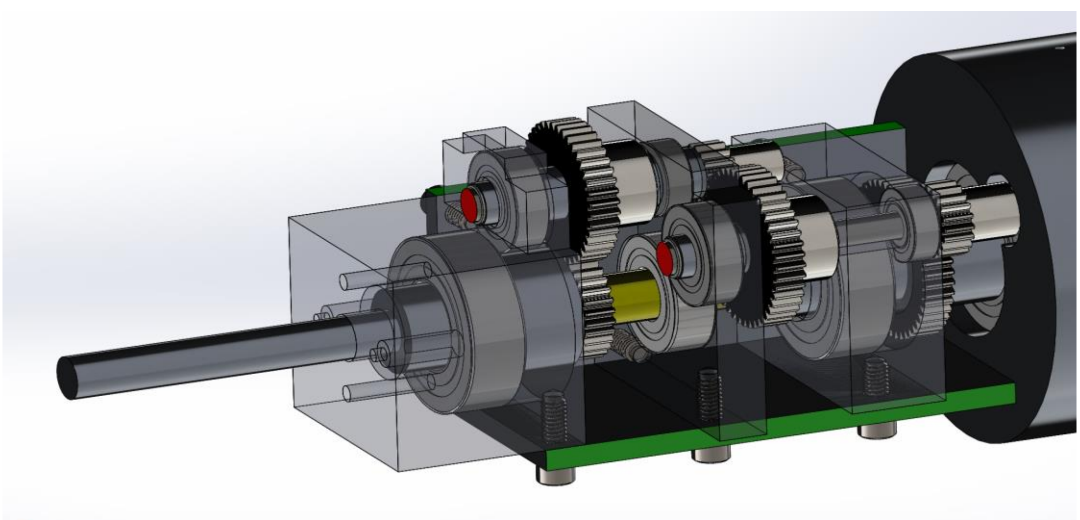


Figure 9: CAD Model of Current Gearbox

Quick-Lock Mechanism

One of our requirements given to us by our sponsors was that our non-propeller module be easy to switch out for the existing propeller system. In order to achieve this goal, we came up with a quick-lock mechanism, detailed in Figure 10a and 10b below. This mechanism works by pushing a spring loaded button on the back plate of the gearbox which pushes a screw down with it. The entire module can then be lined up with the existing mounting face on the submarine and the screw will fit in the slot. When the button is released, the screw slides up the slot, similar to a chain lock on a door, locking this entire module in place. In order to help support the load of the entire impeller module, four dowel pins will be placed between the module and the mounting face on the submarine. The screw, spring, and other materials for this mechanism will all be made of corrosion resistant stainless steel or aluminum.

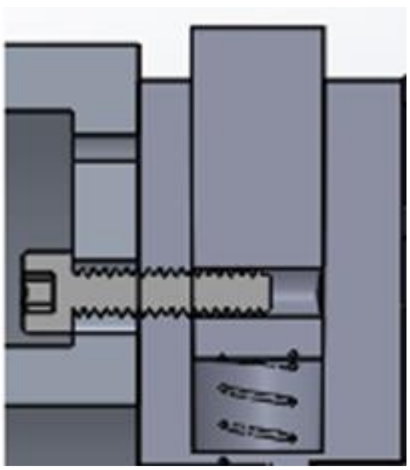


Figure 10a: CAD Model Side View of Quick-Lock Mechanism

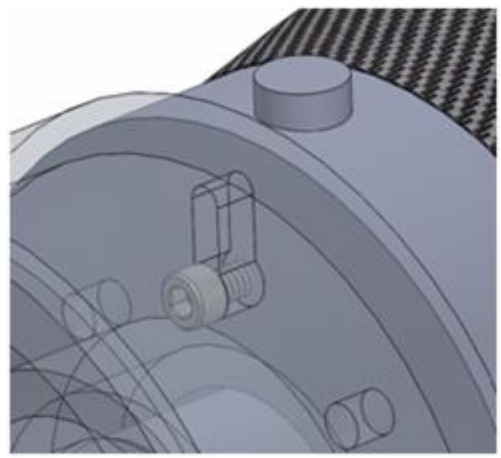


Figure 10b: Isometric View of Quick-Lock Mechanism

Impeller

The last component of our impeller module is, of course, the impeller itself. We needed to design an impeller that could provide enough thrust to propel the submarine forward using the existing drivetrain. In order to determine the dimensions of the impeller and the geometry of the blades necessary to achieve the thrust requires an immense amount of fluid mechanics analysis that we do not have the knowledge of. We were, however, able to obtain a one-month license for a turbomachinery design software called *CFturbo*. Using this software, we input the rpm, flow rate, and head requirements to obtain a design that would meet these requirements. We varied input parameters to get six different impeller designs. With the help of our sponsor, we 3D printed the 3 most promising designs and constructed a test mechanism to measure the amount of thrust that each impeller could produce. The rig consisted of a DC motor, power supply, nozzle, impeller, impeller shroud, supports, and spring scale (Fig. 11). We operated the test rig in the ENGR100 lab tank. With the impeller and nozzle underwater, we supplied the DC motor with 350watts of power, and recorded the thrust as measured by the spring scale. Using a strobe tach we recorded the rpm of the impeller while operating at 350watts. We found that the theoretical speed of the impeller at a given power input, as provided by CFturbo, was accurate. This test allowed us to verify the rpm, power consumption, and thrust of the proposed impeller designs. ImpellerV6 produced the most thrust at 4lbf; which was approximately ⅓ of the theoretically calculated thrust. The discrepancy between theoretical thrust capability and actual thrust generated could be caused by the motor not providing as much power to the impeller as predicted or by the impellers not producing the flow rates that they were designed to produce at the tested power input. We believe that even with 4lbf of thrust we can accomplish our goal of at least 2.56knots (Eq. 1). Using ImpellerV6, which spins at 2000 RPM, we then designed the rest of the module based off of this impeller. A model of this impeller can be seen in Figure 6a below. The impeller and the stators after the impeller will be 3D printed.

$$V = \sqrt{2F_D/(C_D \rho A)} \qquad \text{Eq. 1}$$

Where V is velocity, $\rho$is density, C_D is the coefficient of drag, A is the frontal area, and F_D is the drag force which is equal to the thrust produced. After the water passes through the ducting and into the impeller, the water flows outward from the impeller through the ducting and out towards the back end of the submarine. In this portion, we've added vanes to straighten the flow of water to increase thrust. This can be observed in Figure 12b below.

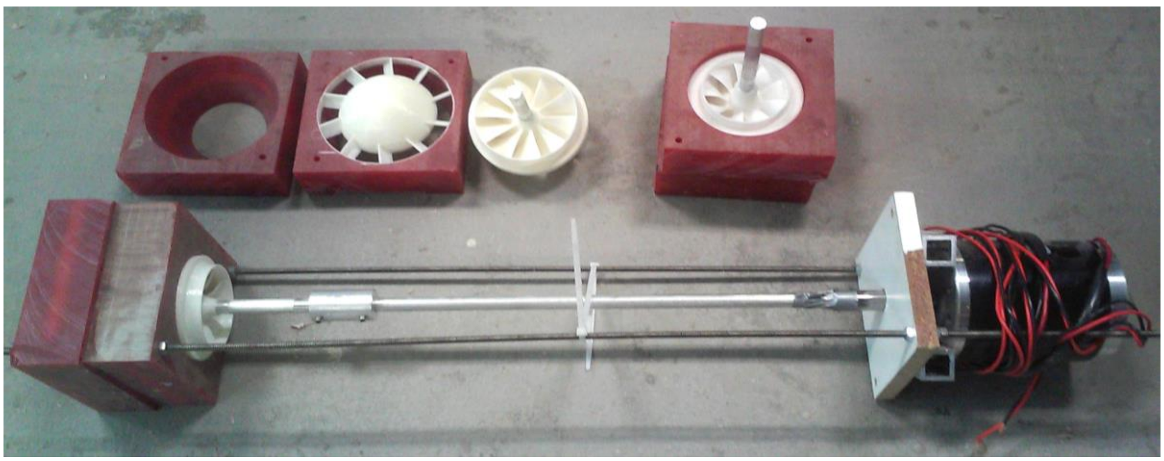


Figure 11: The test rig shown with the additional nozzle, stator, and impeller sets

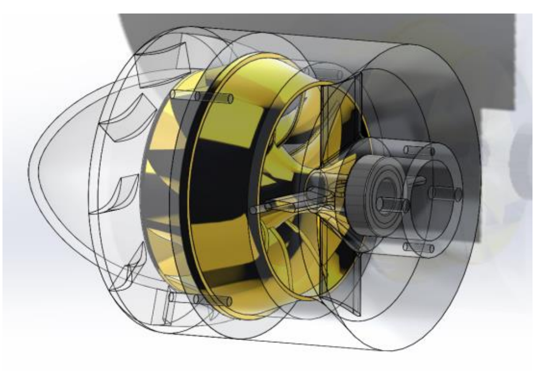


Figure 12a: 2000 RPM Impeller Model

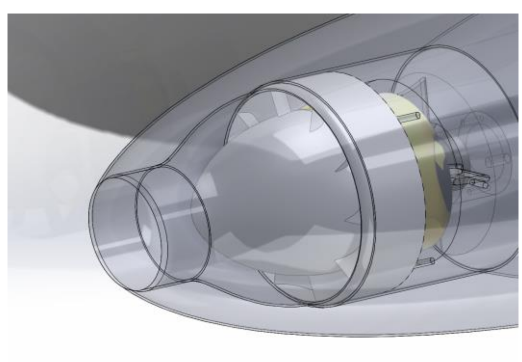


Figure 12a: 2000 RPM Impeller Model

Engineering Analysis

Impeller Design

The impeller has been designed to generate as much thrust as possible with 350W of power input. Each iteration of design requires two steps. The first step is to design the impeller in CFturbo. The second step is to use an Excel function that we made to design the nozzle and predict how much thrust that the impeller and nozzle can generate. The Excel function also allow us to compare impeller characteristics such as rpm, size, and velocity vectors.

The impeller design starts in CFturbo at the setup screen; where the rpm, flow rate, head, fluid type, and efficiency are input (Fig. 13). RPM is the shaft rotation rate at the output of the gearbox. Impellers that spin faster tend to be smaller. The head is the pressure differential that impeller creates and that it is designed to operate at. The head determines how much the nozzle can constrict and accelerate the flow, therefore a greater head allows for a greater exit flow velocity. The volume flow rate determines the mass flow rate of the water. Together the mass flow rate and exit velocity determine the thrust. The fluid that our impeller operates in is always water. The next step is define the hub diameter, for the input shaft, and to allow CFturbo determine the appropriate dimensions (Fig. 15). The final step is to input how many blades the impeller will have (Fig. 14). CFturbo will make a suggestion as to how many blades are necessary for the flow through the impeller to follow the geometry. Ideally the impeller would have an infinite number of infinitesimally thin blades. In reality 6-11 blades are frequently used. CFturbo is now able to generate a 3D model of the impeller (Fig. 16)

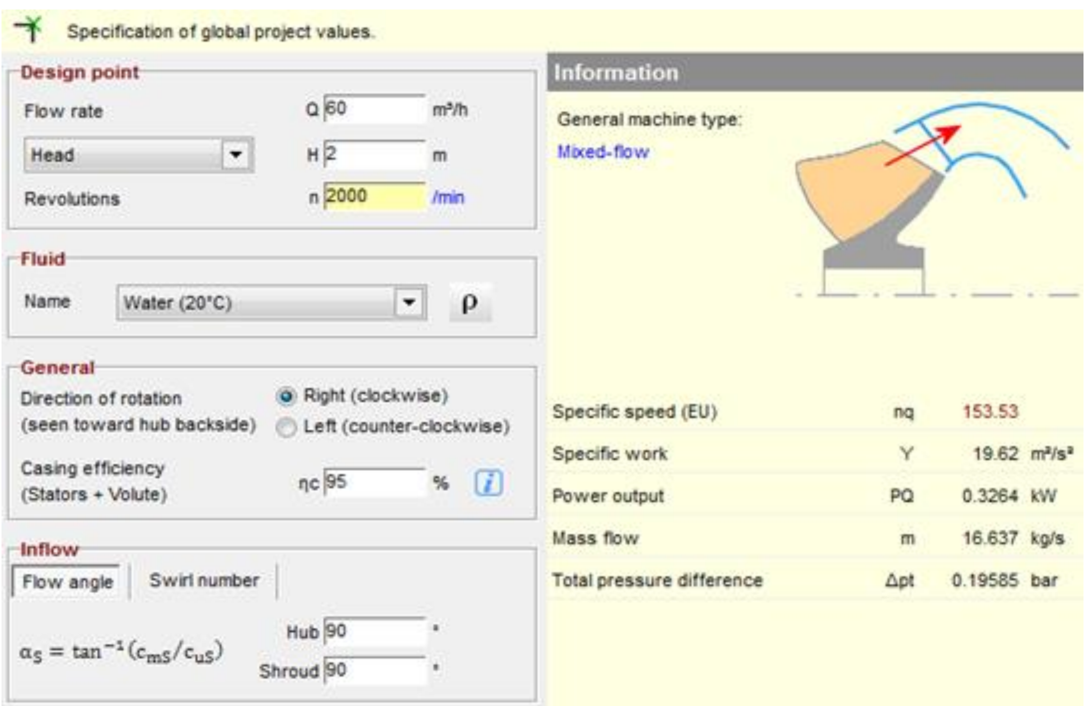


Figure 13: The "Global Project Values" menu allows for the designation of variable that apply to all stages of the design process.

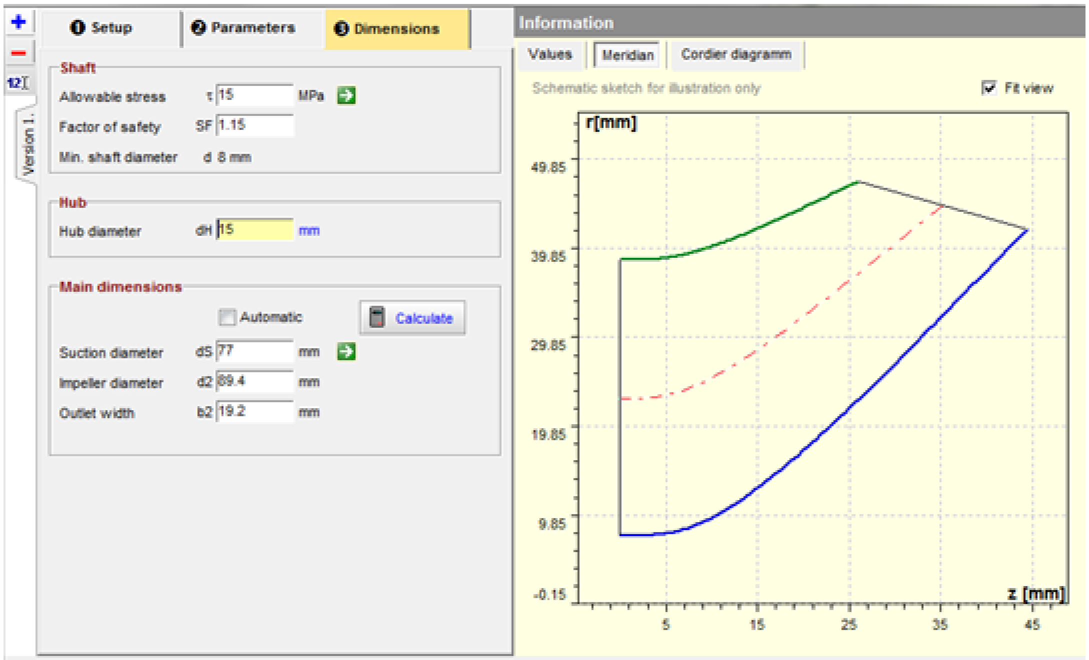


Figure 14: The “Impeller Dimensions” menu can be used to specify the shaft material and the overall size of the impeller.

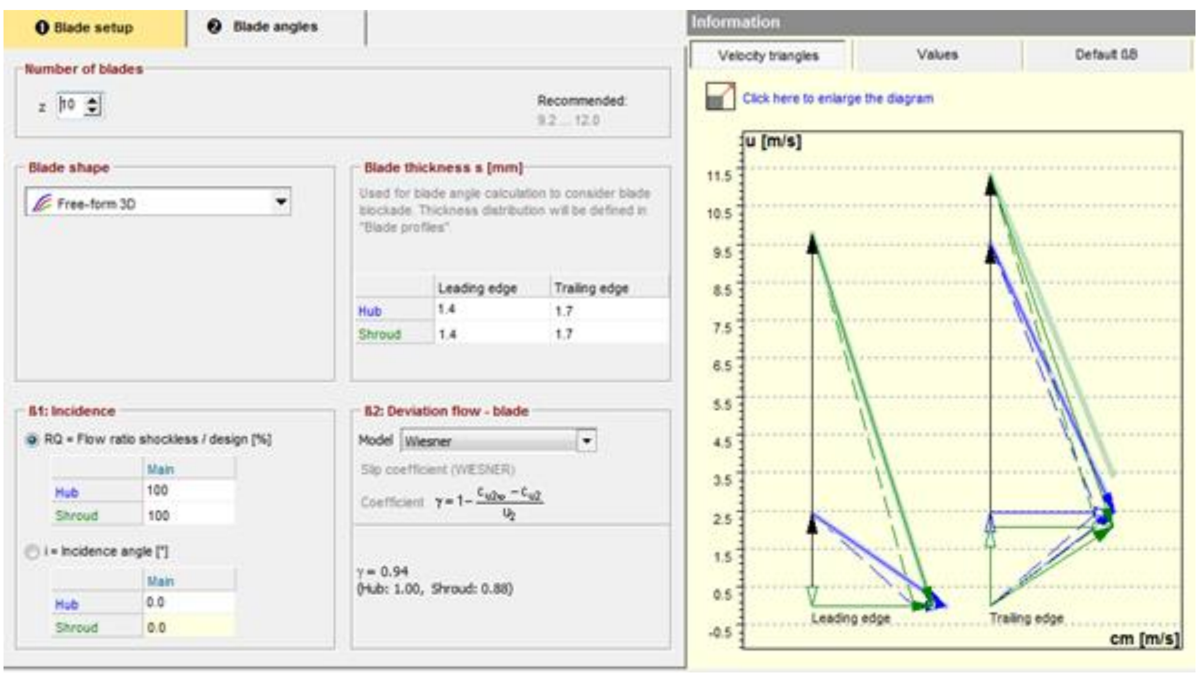


Figure 15: The “Blade Properties” menu allows for the manipulation of the blade thickness, angles, and the number of blades.

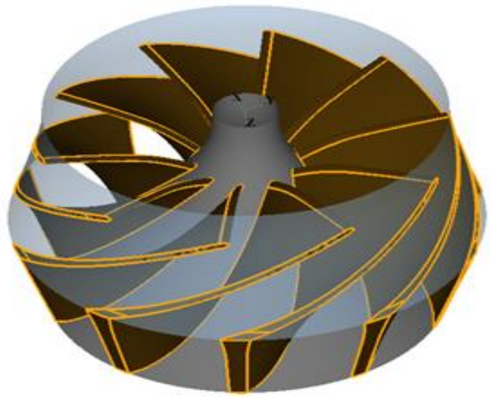


Figure 16: CFturbo generates an interactive 3D model of the impeller allowing the user to isolate specific parts of interest.

Using the impeller characteristics from CFturbo the nozzle is designed using the Navier-Stokes equations for incompressible flow. The equation has been solved for outlet velocity (Eq. 1).

$$\sqrt{\frac{2\Delta P}{\rho} + {V_1}^2} = V_2 \quad \text{Eq. 2}$$

Where ΔP is the pressure change (Pa) caused by the nozzle, ρ is the density (kg/m^3) of the fluid, V_1 is the water velocity (m/s) out of the impeller, and V_2 is the outlet velocity (m/s) of the nozzle. The pressure change was selected to be 80% of the impeller head pressure, as some of the head pressure would be lost to the ducting and vanes. The thrust is then calculated using the mass flow rate through the impeller and the outlet velocity (Eq. 3).

$$\dot{m}V = T \quad \text{Eq. 3}$$

Where $\dot{m}$ is mass flow rate (kg/s), V is outlet velocity (m/s), and T is thrust (N). These equations have been implemented in Excel (Fig. 8). The top three designs, the ones that we will conduct thrust generation tests for are: V3, V4, and V5.

Table 2: Impeller Characteristics in Excel

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	rho	1000	head %	0.80									
2		RPM	HEAD (Pa)	m dot (kg/s)	Power (W)	OD (mm)	B1 (mm)	A_1 (mm^2)	C_m (m/s)	exit vel(m/s)	nozzle OD	A_2 (mm^2)	thrust (N)
3	V1	2700	49000	8.30	408	83.0	14.7	0.0038	2.7	9.26	0.038	0.0011	76.8
4	V2	2000	34300	9.70	333	94.0	16.5	0.0049	2.2	7.73	0.042	0.0014	75.0
5	V3	1320	15000	16.60	326	131.0	34.5	0.0142	2.0	5.29	0.083	0.0054	87.8
6	V4	1620	15000	16.60	326	99.4	26.0	0.0081	3.0	5.74	0.073	0.0042	95.4
7	V5	1720	18000	15.25	329	96.5	24.1	0.0073	3.0	6.15	0.067	0.0036	93.8

Gearbox Design

The gearbox had to convert 220 RPM to 2000 RPM. The output RPM might change due to the geometry of the impeller, but the theory to design the gearbox remains the same. These are the carbon steel gears selected below.

Table 3: Gears and their Dimensions

No. of Teeth	Module	Bore	Pitch Dia.
45	1	10 mm	45 mm
40	1	10 mm	40 mm
30	1	10 mm	30 mm
20	1	8 mm	20 mm
15	1	8 mm	15 mm

The equation which relates the angular velocity of two gears to their number of teeth is given in the equation below.

$$\omega_a = \omega_b \frac{N_b}{N_a} \qquad \text{Eq. 4}$$

Where ω_a is the angular velocity of the first gear, ω_b is the angular velocity of the second gear, N_b is the number of teeth of the second gear, and N_a is the number of teeth of the second gear.
The drive train has three pairs of gears. The configuration of the gears is given in the figure below.

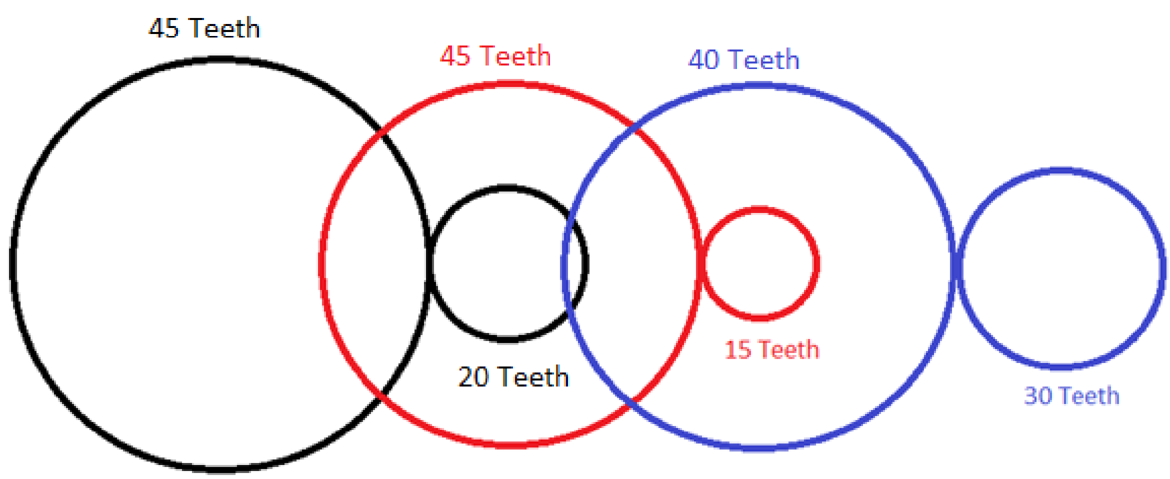


Figure 17: Configuration of the gears in the gearbox. Gears of the same color are meshed together and concentric gears are on the same axle.

From the equation relating the gear angular velocity and number of teeth, we can find that this gear combination converts 200 RPM into 1980 RPM. This the ideal angular velocity for the impeller this gearbox was designed for.

The output velocity can be varied by changing the gears; however, there are two constraints which must be taken into consideration. The gears must be packaged in a diameter as close to 4.5 inches as possible, and the gears must not mechanically fail.

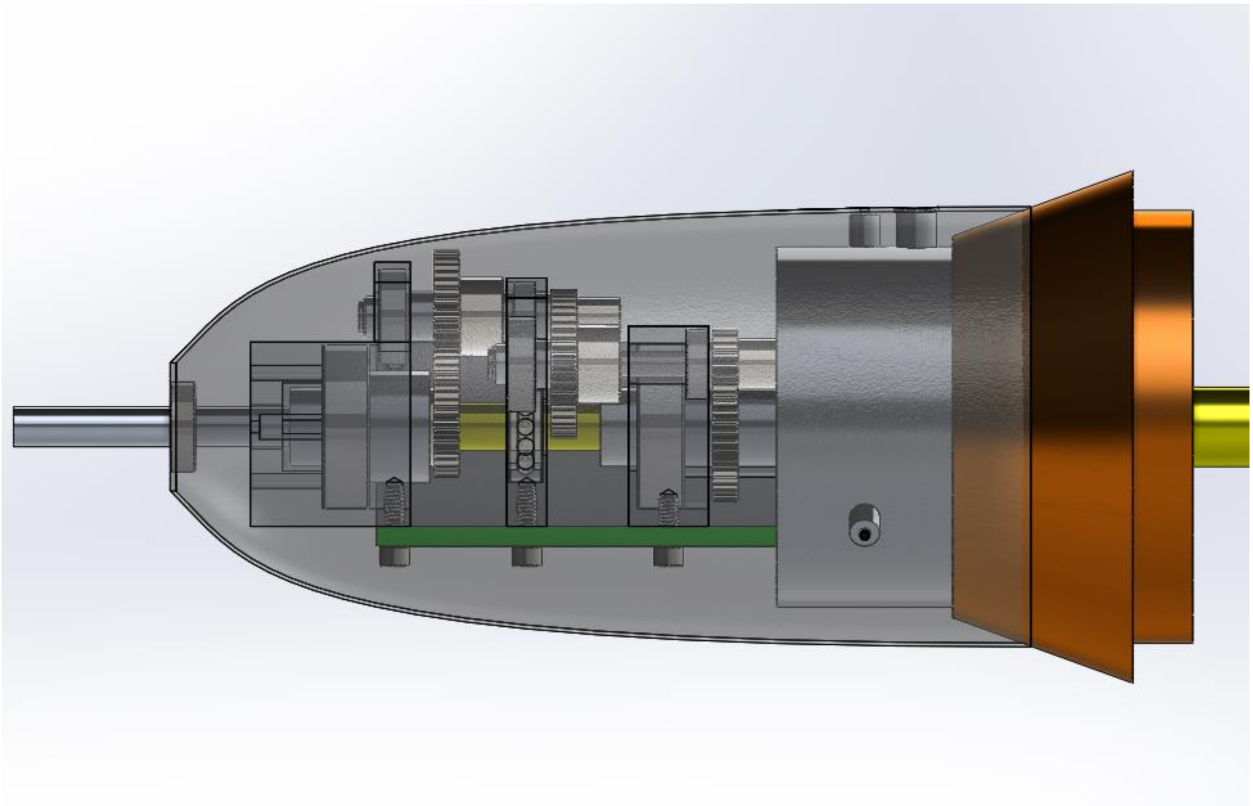


Figure 18: Packaging of the gears

We were able to fit the gears into the space. To do this we used carbon steel gears which allowed us to use smaller gears and made the cowling around the gear-box larger. We were thus able to obtain the sloped in shape of the cowling that is ideal for water flow.

To make sure that the gears won't mechanically fail, the calculated max torque are compared to the allowable torque of the gears, provided by the manufacturers. The torque decreases as the angular velocity increases. The equation relating torque and number of teeth of two gears is given below.

$$\tau_a = \tau_b \frac{N_b}{N_a} \qquad \text{Eq. 5}$$

Where τ_a is the torque of the first gear, τ_b is the torque of the second gear, N_b is the number of teeth of the second gear, and N_a is the number of teeth of the second gear. From this equation we can find the torque acting on each gear. To calculate the input torque, we assume that the pilot can generate about half a horsepower of power at about 200 RPM. This comes out at about 17 Nm. The applied torque and the allowable torque of each gear is put in the table below.

Table 4: Torque acting on each gear and the allowable torque.

Module	No. of Teeth	Torque Acting on Gear	Allowable Torque
1	45	17 Nm	42.26 Nm
1	20	7.56 Nm	14.22 Nm
1	45	7.56 Nm	42.26 Nm
1	15	2.12 Nm	3.267 Nm
1	40	2.12 Nm	42.26 Nm
1	30	1.89 Nm	8.96 Nm

By switching to carbon steel, we were able to design a gear-box that fit within our required dimensions and provide a safety factor of at least 1.54 for each of the gears.

Mockup

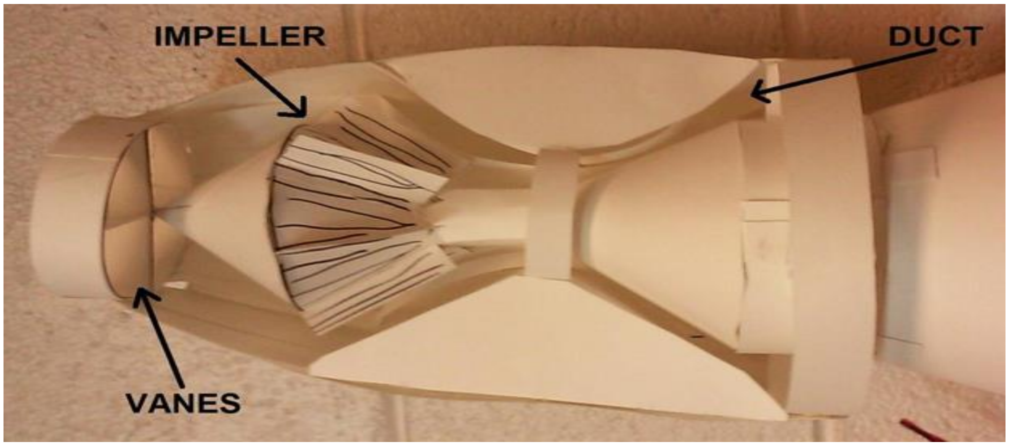


Figure 19: As shown in the Mock-up design, the primary three components are the impeller, duct, and vanes.

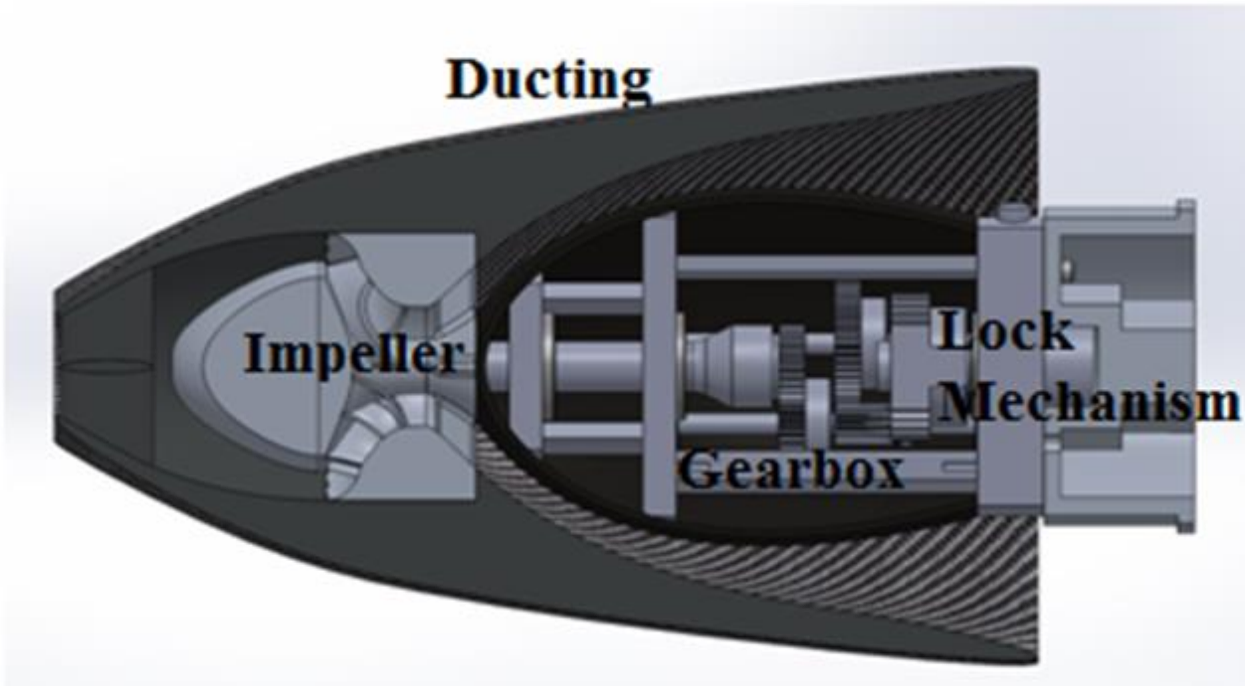


Figure 20: The preliminary design in CAD

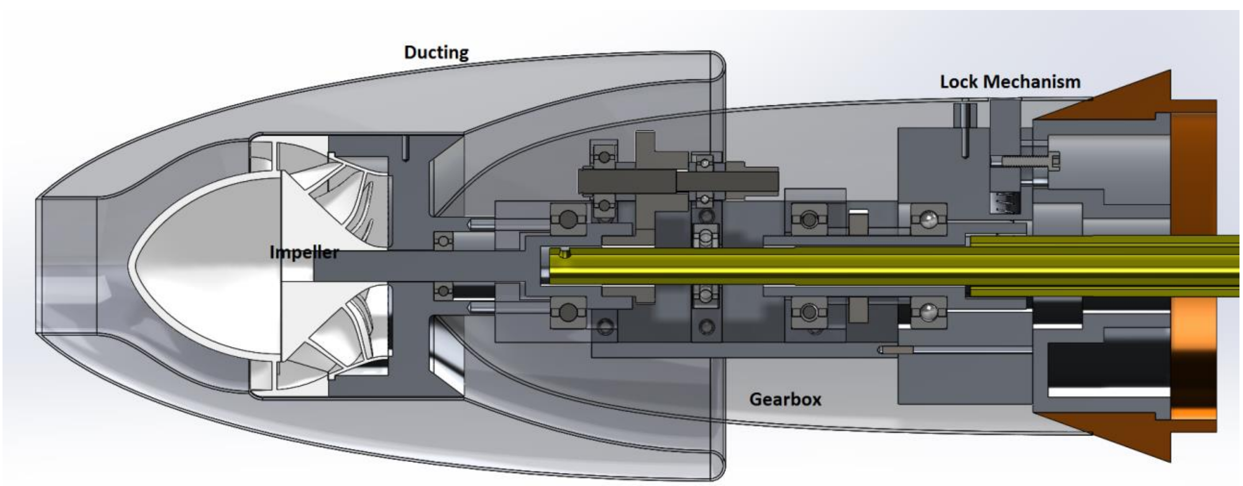


Figure 21: Final Design in CAD

Our mockup was very similar to the initial CAD design. The main difference is that we didn't anticipate the size of the gearbox.

Empirical Testing

Our sponsors performed a test to verify that fused filament 3D printing would result in parts strong enough for full speed tests of our top impeller designs. The impeller was attached to a shaft and

DC motor, then rotated at full speed (Fig. 14). The test proved that fused filament 3D printed parts are suitable for our future thrust generation tests.

Figure 22: Prototype Impeller

FMEA

Table 5: FMEA of Waterjet Propulsion System

Risk Item	Effect	Cause	Likelihood (L) 3=high 1=low	Severity (S) 3=high 1=low	Importance (I) I=L*S	Action to minimize risk
Impeller is damaged	Thrust cannot be produced	Intake of solid object into impeller	1	2	2	Make spare impellers
Impeller doesn't produce enough thrust	"Sufficient" thrust cannot be produced	Impeller not designed to available power	2	3	6	Test 3D printed impellers early on, to verify the power required at the operating conditions

Quick-lock fails	Thrust module cannot be secured to the submarine	Binding of interlock	1	2	2	Design with sufficient clearances so that binding is very unlikely
Gears	Gears Break	Sudden, high torque is applied	1	3	3	Design the gearbox with a high safety factor

According to our FMEA (Table 3), the risk of the impeller not producing enough thrust is our greatest risk. We gave it a medium chance of happening because at this stage, we have not verified that the impeller can produce enough thrust. Also a waterjet system has not been used in the human powered submarine competition before, so we do not have a clear benchmark to compare our impeller too. If the the impeller does not provide enough thrust to move the submarine, that would be very serious. The waterjet system must be able to at least move the submarine, and it must move the submarine at 2.52 knots to meet our engineering specifications. To minimize this risk, we will set up a test rig to measure the thrust produced by the 3D printed impellers.

The next most serious risk is if the gears break. The reason this is serious is because if the gears fail, the impeller will not spin and no thrust will be produced. To minimize the risk, the input torque must be properly measured, and the gearbox designed with a high safety factor.

Current Challenges

The difficult part of our design lies in determining the optimal impeller design for our purposes, due to the complexity of the impeller design. While we are sure about the structure of our design, we are not yet sure of the final impeller design, as the impeller we choose will impact the way we design our transmission and duct. So far, we've relied on computer simulations. Based on computer modeling, we have come with three potential impeller designs via 3D printing, each made to hopefully produce the thrust we want. To get a feel of the impeller's actual performance, we have to experiment on these designs, each of different sizes, with each producing a different output speed and thrust. Once we are sure of the impeller design and thrust we will use, it becomes a matter of optimizing our gear transmission, hoping we can translate their performance into the thrust we ideally want. Most importantly, we have to make sure the duct is designed well in that it can allow the impeller to produce constant acceleration to maintain the thrust.

As of now, our only challenge is time to manufacture certain parts along with time to assemble the module. We have already settled on an impeller design after testing it. There are still a few parts that have yet to be manufactured. We still need to make the mold for our ducting, and then lay out the fiberglass composite in the mold to create the actual part. Those process will take time, but we should be able to assemble our module and have it tested in time for DR 5.

Manufacturing Plan

Manufacturing plans are attached as separate documents in Appendix F.

Ducting

The ducting will be constructed out of fiberglass composite. Our sponsor will use a CNC router to make tooling board molds. We will paint and finish these molds. Our sponsor will then use the vacuum bag layup technique to make the actual fiberglass composite parts. Some advantages of using fiberglass composite and molding the ducting are that it will be lightweight and relatively cheap to make. One disadvantage is that the mold making process takes a large amount of time.

Gearbox

The gearbox casing will be made of fiberglass composite in the same way as the ducting. The gears will be sourced from SDP/SI. The gears are Carbon Steel so they will need to be chrome plated before assembly. The aluminum supports will be milled. The stainless steel shafts will be sourced from McMaster and parted to length on a manual lathe. We will then attach all of the gears together with the shafts and bearings and fit them into the gearbox casing. One advantage to this process is that, as mentioned above, the fiberglass will be lightweight and cheap to make. All of the aluminum and stainless steel parts will be corrosion resistant. One downside to this is the lengthy process of molding the gearbox casing.

Impeller

The impellers will be constructed with 3D printing. The advantage of the 3D printing is that we don't need to pay for the impeller to be made on a 5-axis CNC mill. The disadvantage is that 3D printed parts aren't as strong.

Quick-Lock Mechanism

The quick-lock mechanism will be made out of a stainless steel screw and spring and aluminum rod, sourced from McMaster. The aluminum component will require manual mill and lathe operations. One advantage to this process is that is made from very few parts and will be easy to assemble. One disadvantage would be that the parts are very small and may not be durable.

Exploded Views

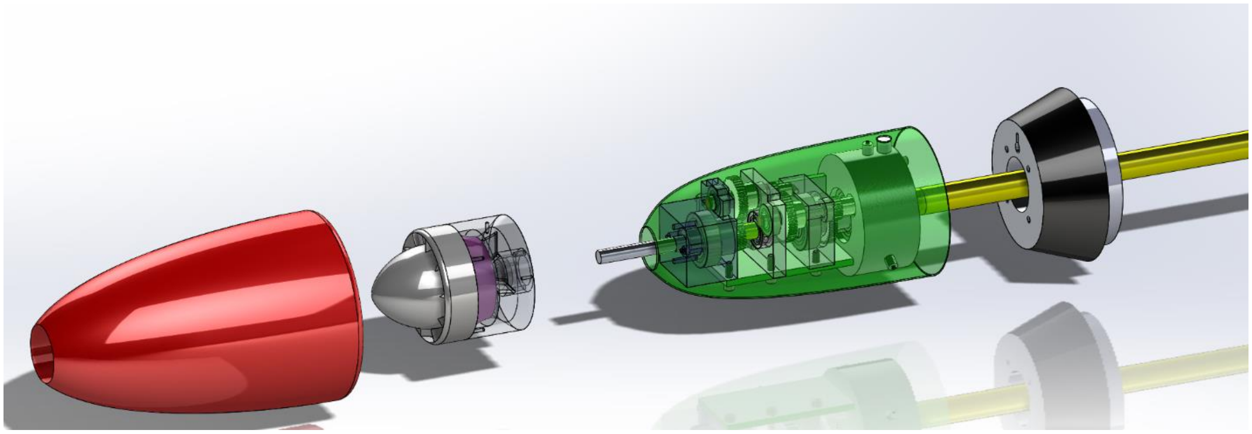


Figure 23: Exploded View of Sub-Assemblies

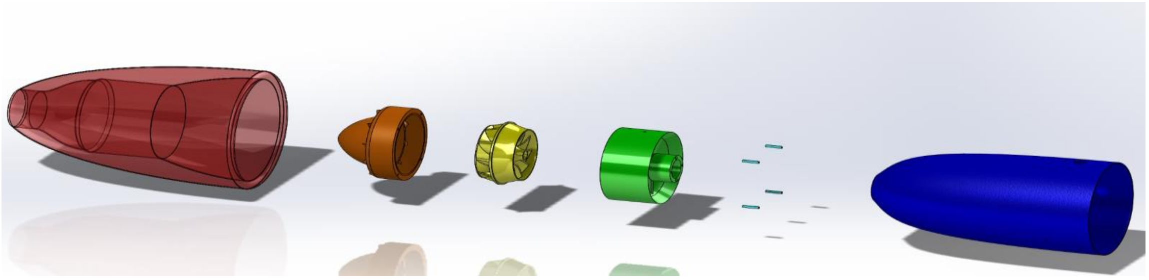


Figure 45: Exploded View of Impeller

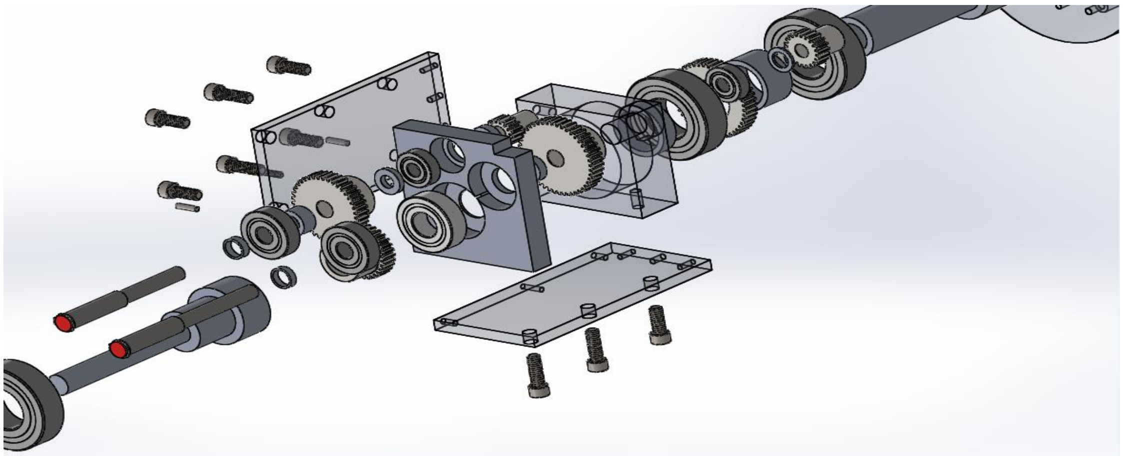


Figure 25: Exploded View of the Gearbox

Completed Prototype

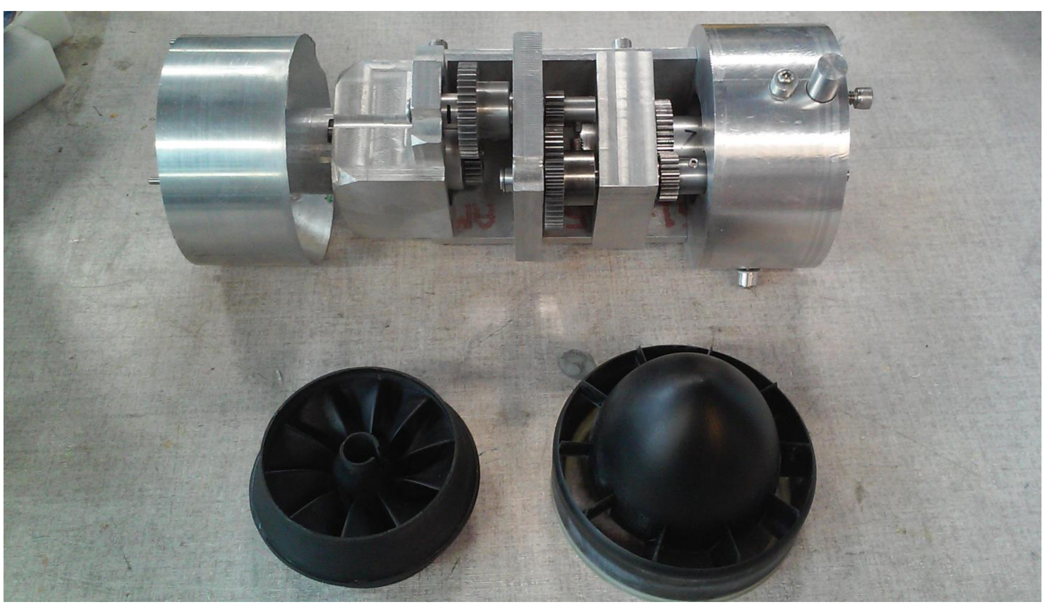


Figure 26: Gearbox and Impeller

Figure 27: Prototype with Cowling, Gear-Box Cover Off

Figure 28: Prototype with Cowling

Engineering Change Notice

We put the ECNs in appendix C. The main change is that we forgot to add the key-ways and set screws to attach the impeller and gears to the shafts. Also drainage holes were added to the cowling so that it could fill with water and drained. Otherwise, there were no design changes since we went through several iteration of the design to make sure that everything was fitting together.

Validation Protocol

To prove that our design has met or exceeded the engineering specifications, we will validate our device with a series of tests and inspections. As seen in Table 4 we have already begun validating our design.

Table 6: Validation Methods

Specification	**Validation Method**	**Completed**
Thrust Without Propeller	Inspection by ISR judges	Yes
Sufficient Thrust	Empirical Thrust Testing	No
Mass and Center of Gravity	Inspection of CAD model	Yes
Easy Switch Out	Demonstration	No
Corrosion Resistance	Inspection of materials	No

To validate that the impeller design would be defined as a non-propeller propulsion mechanism, we contacted the ISR judges and confirmed that an impeller propulsion is defined as a water-jet not a propeller. To validate the specification of sufficient thrust to reach 2.52 knots we originally planned to test our impeller design on the submarine in the Marine Hydrodynamics Laboratory (MHL). Unfortunately, the MHL has a leak and will be drained for repairs through the end of April. We now plan to plan to validate this requirement by measuring the thrust generated. This will be performed in a similar fashion to the test for determining which impeller to use. We will suspend the impeller module in the ENGR100 test tank, power the gearbox with a DC motor, and measure the thrust force with a simple spring scale. Using the measured force, the known coefficient of drag of the submarine, and the drag force equation from DR4 (Eq. 1, pg. 12) we will predict the top speed of the submarine. The specification for mass and center of gravity have been verified in Solidworks by comparing the computed center of gravity and mass of our impeller module with that of the propeller module. The mass and center of gravity are within 5%. To validate that our device is easy to switch out we will time a demonstration of removing the propeller module and attaching the impeller module. The demonstration must take less than 20 minutes, involve three or fewer people, and use only basic tools such as screwdrivers, mallets, wrenches. To validate that the impeller module is corrosion resistant, the materials used will be inspected and verified that they are corrosion resistant. With the exception of the carbon steel gears, we have met this specification. We intend to chrome plate the gears to make them corrosion resistant, however it takes two weeks to get parts chrome plated, therefore we will chrome plate them after the design expo.

Design Critique

Present an honest critique of your design. Did you meet all of your specifications? If not, was the result still acceptable or does more work need to be done? Did any particular element(s) work much better/worse than expected? Why?

The non-propeller system met all specification except that of corrosion resistance. The high carbon steel gears are the only components not made of corrosion resistant materials. Those gears were meant to be chrome plated to prevent corrosion, however the lead time for chrome plating did not allow for the gear to be chrome plated between design reviews. As such, there are plans to chrome plate the gears after the close of the semester. Surface rust did develop on the gears during underwater test sessions, subsequently the rust was removed to prevent further rusting. The rust that did form during the semester was deemed minimal and non-compromising to the function and integrity of the gears.

The impeller could have been designed with a larger diameter, which would have decreased the RPM requirement. A significant decrease in RPM required would have allowed for fewer gears in the gearbox, thus greater efficiency in power transmission. The reason that the impeller was not designed larger was due to the print size limitation of the 3D printer available for making the impeller design. Had a larger printer been available, the impellers would have been designed larger, operating at a lower RPM.

The actual thrust generated by the impeller was 35% of the theoretical thrust calculation. The theoretical calculation did not account for fluid resistance within the ducting, backflow around the impeller, and discrepancies in the actual power being imparted to the moving fluid. Even with the significant reduction in thrust, the specification for sufficient thrust was met.

Future Work

If you had the time and resources to continue the project, what are the very first things your team would change about your design or methodology? What are the broader implications of your project moving forward? Refer back to your background section to remind the reader of where your work fits into the overall context of the design problem.

If given the time and resources to continue the project, the impeller design would be updated to a larger diameter impeller, reducing the required output RPM and the number of gears in the gear box. This design change would make the system more efficient, overall.

The gears still need to be chrome plated so that they are corrosion resistant. Originally the plan was to use stainless steel gears, but from the analysis, it was found a stronger material such as carbon steel was needed. It takes about two weeks to chrome plate gears.

This propulsions system is a finished product, which means that the University of Michigan Human Powered Submarine team will be using it in the ISR competition. The true validation of the system will be how well it performs at the competition.

Team Member Biographies

Jonathan Kim
I am a junior in mechanical engineering at the University of Michigan. I have always been interested in cars and would like to work in the automotive industry.

Jonathan Meines
4th Year Mechanical Engineering
Member of HPS since 2011
Assistant Product Developer at In2being, llc

Paolo Torres
4th Year Mechanical Engineering
Interested in mechanical engineering design, manufacturing, and would like to one day work the field of robotics

Saketh Samaymantri
4th Year Mechanical Engineering
I am a senior studying Mechanical Engineering with a great interest in the design field, and hope to work in either the automotive or aerospace industry

Works Cited

[1] Polowy, Steven. "Human Powered Submarine." Human Powered Submarine - WSTPC. U of M College of Engineering, n.d. Web. 25 Jan. 2015.

[2] *Engineering Design Handbook - Wheeled Amphibians*. N.p.: n.p., 1971. Print.

[3] Rawson, K. J., and E. C. Tupper. *Basic Ship Theory*. Oxford: Butterworth-Heinemann, 2001. Print.

[4] Carlton, J. S. *Marine Propellers and Propulsion*. Amsterdam: Elsevier Butterworth-Heinemann, 2007. Print.

[5] "Biomimetics and Marine Technology" *Marine Technology Society Journal* 45 (July-Aug. 2011): n. pag. *Marine Technology Society*. Web. <https://www.mtsociety.org/Files/pdf/publications/journal/MTS%2045-4.pdf>.

[6] Gaessner, Dustin, David Price, and Jeff Campana. *Odin's Revenge*.*International Submarine Races*. N.p., 2011. Web. 25 Jan. 2015. <http://www.isrsubrace.org/docs/11th/ISR11-UCSD-Technical-Report-Odin%27s-Revenge.pdf>.

[7]"Outstanding Innovation Award for Students of Rhine-Waal University of Applied Sciences." *: Hochschule Rhein-Waal*. N.p., n.d. Web. <http://www.hochschule-rhein-waal.de/nc/en/pressemitteilungen/presse-details/article/outstanding-innovation-preis-fuer-studierende-der-hochschule-rhein-waal.html>.

[8] "Project Taniwha: A Human-powered Submarine." *The University of Auckland*. N.p., n.d. Web. <http://www.abi.auckland.ac.nz/en/about/our-research/biomimetics/taniwha.html>.

[9] "Design and Specifications." (n.d.): n. pag. *International Submarine Races*. École De Technologie Supérieure, 2009. Web. 25 Jan. 2015. <http://www.isrsubrace.org/docs/10th/10th_ISR_OMER_6_competition_report.pdf>

[10] Gusler, Carl P. Method of Using a Linear Propulsor Array for Propulsion and Navigation. International Business Machines Corporation, assignee. Patent US 7090548 B1. 3 Feb. 2005. Print.

[11] 王硕, 边桂彬, 魏清平, and 谭民. Biomimetic Long-fin Undulatory Propulsion Robotic Fish. 中国科学院自动化研究所, assignee. Patent CN 103213665 A. 24 July 2013. Print.

[12] Rufo, Michael, David Shane, Michael Conry, and Will Ober. Aquatic Vehicle. Boston Engineering Corporation, assignee. Patent US 20140109821 A1. 24 Apr. 2014. Print.

[13] Laser, Otto. Fin Propulsion Boat. Otto Laser, assignee. Patent US 4345903 A. 24 Aug. 1982. Print.

[14] 丛文超, 吴贺贺, and 晋文菊. Cuttlefish Imitated Impulse Type Water Jet Propulsion Unit. 江苏科技大学, assignee. Patent CN 201712781 U. 23 June 2010. Print.

[15] "International Submarine Race Summary." *International Submarine Races*. N.p., n.d. Web. 25 Jan. 2015. <http://www.isrsubrace.org/docs/12th-ISR-Master-Team-List.pdf>.

[16] Yankaskas, Kurt. "International Submarine Races Overview." International Submarine Races. Foundation for Underwater Research, n.d. Web. 25 Jan. 2015.

[17] Glass, Jacob. "The Submarine." MichiganHPS. U of M Human Powered Submarine Team, n.d. Web. 25 Jan. 2015.

[18] SOFGE, ERIK. "Navy SEALs Could Turn Superhuman with Pentagon's PowerSwim." *Popular Mechanics*. N.p., 1 Oct. 2009. Web. <http://www.popularmechanics.com/technology/military/4223354>.

[19] Scott, Peter. "The End of the Hyperfin? The DOL-Fin X-20 Review – DeeperBlue.com." *Deeper Blue.com*. N.p., 13 July 2012. Web. <https://www.deeperblue.com/the-end-of-the-hyperfin-the-dol-fin-x-20-review/>.

[20] "Bionicinspiration.org." *Bionicinspiration.org*. N.p., 24 Nov. 2014. Web. <http://bionicinspiration.org/dolphin-monofin/>.

[21]"Subhuman Project, Man-Powered Sub to Cross Atlantic by Fall 2009 « Kast-A-Way ." Web log post. *KastAWay Blog*. N.p., 29 Apr. 2009. Web. <http://www.kastawayswimwear.com/Blog/index.php/subhuman-project-man-powered-sub-to-cross-atlantic-by-fall-2009/>.

[22] Nguyen, Nam. *Odin's Rage*. *International Submarine Races*. N.p., 2009. Web. 25 Jan. 2015. <http://www.isrsubrace.org/docs/10th/10th_ISR_Report_UCSD_Odin.pdf>.

[23] Swanberg, Seth, Saben Rossi, and Samuel Levinsky. *International Submarine Races #10 Design Report*. *International Submarine Races*. University of Maine, 2009. Web. 25 Jan. 2015. <http://www.isrsubrace.org/docs/10th/10th_ISR_UMaine-HPS-Report-Final-Revision.pdf>.

APPENDIX A

Additional Design Ideas

1) Non-Hobie Wings
In this concept, a set of wings are used to create propulsion. The shafts rotate another set of of shafts using either chain drives or belt drives to create a flapping motion of the wings.

2) Dolphin Tail Driven with Cables
A flexible tail with a wing at the end like a dolphin tail. The tail would be actuated by changing the tension in two cables. The cables would run along the outside of the tail and cause the tail to flex much like a tendon does a finger.

3) Reverse Drag Chute
A "chute" that would be pushed backwards whilst open, then collapse while being pulled forward. This would repeat continuously.

4) Dual Dolphin Tail
The idea behind this concept is that a pair of fins shaped like a dolphin's tail fin are placed in the back of the submarine. Unlike a single fin creating propulsion, each half fin oscillates individually to create thrust.

5) Ducted Oscillating Paddles
In this method, a paddle is housed in surrounding ducts. Theoretically, thrust would be generated by the oscillating paddle, while the ducts can concentrate the direction the thrust is produced.

6) Oscillating Foil Propulsion
This method of propulsion is loosely based of a proposed project from the Defense Advanced Research Projects Agency known as PowerSwim. A worm shaft drives a worm gear, operating a crank-slider mechanism. A foil is attached on a joint at the end of slotted link with a slider. A spring is also used to hold the foil in position.

7) Hobie Fins with Pin Joints
This uses four hobie kayak fins that flap up and down to produce thrust. Pin-joints are implemented to simplify the design. Depending on where the pin-joints which connect to the fins to the shaft are placed, the rotation of the fins can be varied. However since pin joints are used, some of the motion will be perpendicular to the useful motion of rotation.

8) Hobie Fins without Pin Joints
This uses four hobie kayak fins that flap up and down to produce thrust. No pin joints were used. However this made the design infeasible since the arms would get in the way of each other.

9) Impeller/Waterjet with Wide Exit Nozzle
This system uses a partially enclosed impeller to push out the water sucked in through the fron. The exit nozzle is wide to reduce viscous losses.

10) Crank Dolphin Flipper
An crank is used to oscillate the motion of a flipper. The flipper is attached with a point joint.

11) Parachute Propulsion
A crank is used to oscillate back and forth a parachute. The parachute would close when pushed forward and open when pushed backwards, creating net forward motion.

12) Rotating Arms
This method of propulsion works similarly to the freestyle stroke while swimming. The contra-rotating shafts would be connected through gears and a crank to each of the rotating arms which rotate constantly on either side of the submarine. When the arms are in a position to push the water back, there will be a curved surface to push the water until it completes half of the motion. This curved surface will then rotate flat when the arms are rotating back to this position to reduce drag effects

13) Oscillating Wings
This method implements two oscillating wings, shaped like airplane wings, on either side of the submarine that oscillate upwards and downwards through the use of a crank system and a pin join.

14) Piston Water Pump
This method works by having a water inlet that leads to a large piston that is powered by a crank system connected by gears to the existing contra-rotating shafts

15) Magnetohydrodynamic Propulsion
This uses a strong magnetic field to propel water by electrification.

16) Rotating Buckets that Displace Water
This method works similarly to the rotating arms concept except that it actually uses buckets to displace the water.

17) Waterjet with Rotating Case
A waterjet driven by an enclosed impeller attached to the case, such that the case would rotate with the impeller. This idea is simple since the case and impeller can be directly attached to one another and rotate together. However, having the case spin would lead to viscous losses.

18) Waterjet without Rotating Case
A waterjet driven by a semi-enclosed impeller. The impeller case would be stationary. Water is taken in through one end, and with the use of an impeller, accelerated and moved out the other end.

19) Double Hobie Drive
A system utilizing two pairs of hobie fins. The fins would be actuated from rocker linkages. The two pairs of fins would be placed such that the net force vector would only be backwards.

20) Vertical Flipper

In this concept, a mono-fin is used to generate thrust. Each shaft rotates a crank-rocker linkage that will oscillate the fin, imitating how a dolphin propels itself. Unlike the first concept, this does not use a network of cables.

APPENDIX B

Bill of Materials

Material Description	**Quantity**	**Manufacturer**	**Part #**	**Cost**	**Manufacturing Process**	**Assembly Process**
Stuff						
Type 302 Stainless Steel Compression Spring	1	McMaster-Carr	1986K78	$5.01		
10-24 Stainless Steel 3/4" Socket Head Cap Screw 25 Pack	1	McMaster-Carr	92185A245	$5.48		
18-8 Stainless Steel Dowel Pin 3/16" Diameter, 1"long, 20 Pack	1	McMaster-Carr	90145A510	8.07		
18-8 Stainless Steel Dowel Pin ¼" Diameter, 0.75" long, 10 Pack	1	McMaster-Carr	90145A540	5.67		
6-32 Stainless Steel 1/2" Socket Head	1	McMaster-Carr	92185A148	2.74		

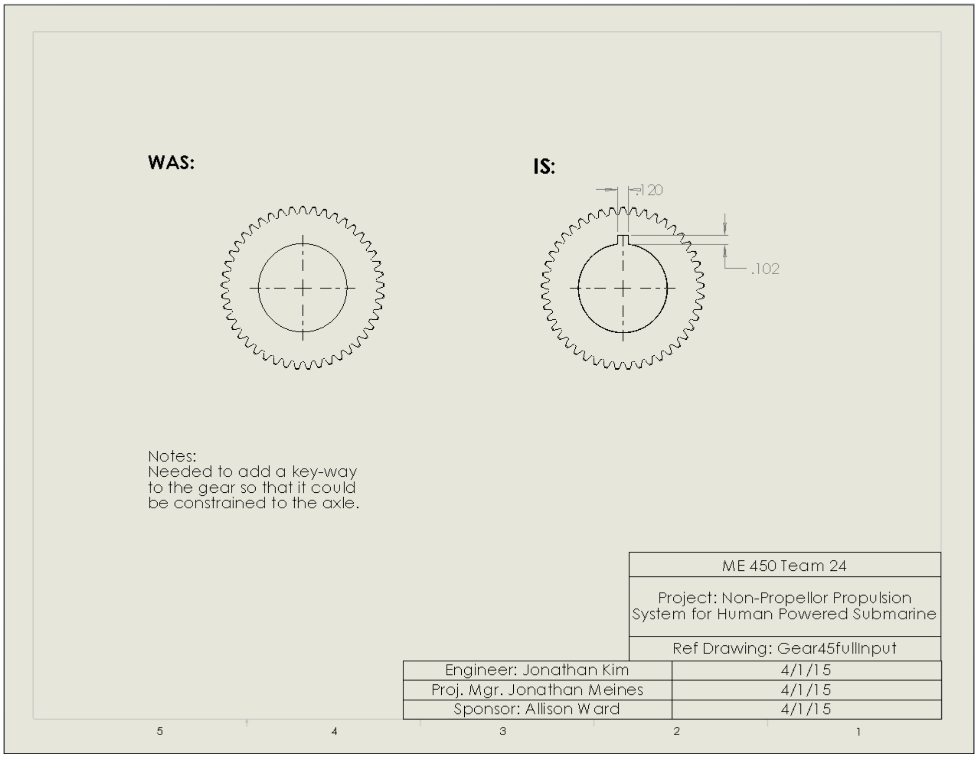
Cap Screw 25 Pack						
316 Stainless Steel Dowel Pin ⅛” Diameter, 0.75” long, 10 Pack	1	McMaster-Carr	97395A451	8.12		
Tooling Board	6	Huntsman	Donated drops	N/A	CNC Router	Adhesive
MEKP	2	Fibreglast	69-A	2.95	Mixing	
Duratec	1	Fibreglast	1041-B	129.95	Spray application	
Epoxy Resin	1	West Systems	105	58.95	Lay-up	
Fiberglass	1	Fibreglast	1094-C	49.45	Lay-up	
Release Film	1	Fibreglast	1058-C	29.95	Lay-up	
Vacuum Bag	1	Fibreglast	1678-C	19.95	Lay-up	
Printer filament	1	Digitide	483621	18.84	Fused Filament	
Gears						
15 pitch diameter Carbon Steel spur gear	1	SDP/SI	A 1C 2MY10015	$14.31		
20 pitch diameter	1	SDP/SI	A 1C 2MY10020	$14.89		

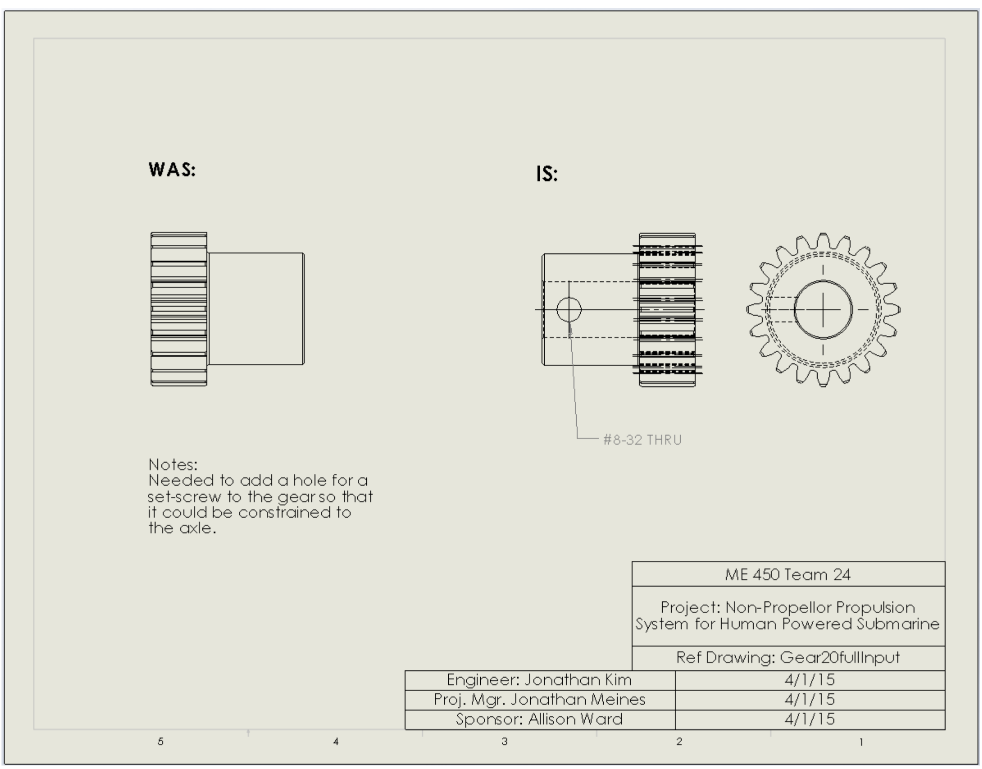
Carbon Steel Spur Gear						
30 pitch diameter Stainless Steel Spur Gear	1	SDP/SI	A 1C 2MY10030	$18.18		
40 pitch diameter Stainless Steel Spur Gear	1	SDP/SI	A 1C 2MY10040	$21.56		
45 pitch diameter Stainless Steel Spur Gear	2	SDP/SI	A 1C 2MY10045	$22.91		
Bearings						
8 mm Diameter Stainless Steel Bearing	2	McMaster-Carr	6153K71	$13.54		
10 mm Diameter Stainless Steel Bearing	2	McMaster-Carr	6138K74	$31.53		
15 mm Diameter Stainless Steel Bearing	1	McMaster-Carr	6153K76	$33.75		
25 mm Stainless Steel Bearing	3	McMaster-Carr	6153K79	$45.40		

Raw Stock						
0.5" Diameter 6061 Aluminum Rod	4”	In-Stock	N/A	N/A		
5" Diameter 6061 Aluminum Round Stock	12”	Kaiser Aluminum	N/A	N/A	Mill and Lathe	Fasteners
1/4" Aluminum Sheet Metal	24” x 24”	Kaiser Aluminum	N/A	N/A	Mill	Fasteners
6" Diameter Aluminum Round Stock, 6" length		Kaiser Aluminum	N/A	N/A	Lathe and Mill	Fasteners

APPENDIX C

Engineering Change Notices





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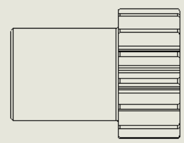

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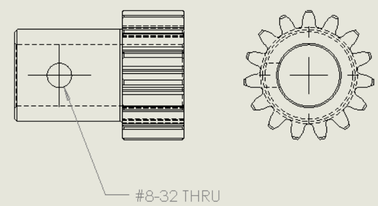

Notes:
Needed to add a hole for a set-screw to the gear so that it could be constrained to the axle.

	ME 450 Team 24
	Project: Non-Propellor Propulsion System for Human Powered Submarine
	Ref Drawing: Gear15fullInput
Engineer: Jonathan Kim	4/1/15
Proj. Mgr. Jonathan Meines	4/1/15
Sponsor: Allison Ward	4/1/15

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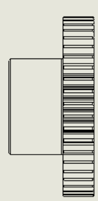

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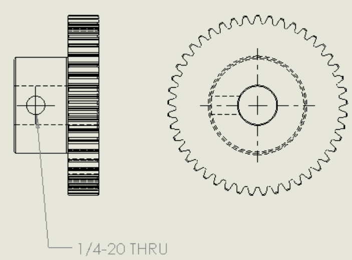

Notes:
Needed to add a hole for a set-screw to the gear so that it could be constrained to the axle.

	ME 450 Team 24
	Project: Non-Propellor Propulsion System for Human Powered Submarine
	Ref Drawing: Gear45fullInput2
Engineer: Jonathan Kim	4/1/15
Proj. Mgr. Jonathan Meines	4/1/15
Sponsor: Allison Ward	4/1/15

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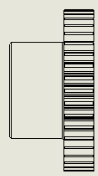

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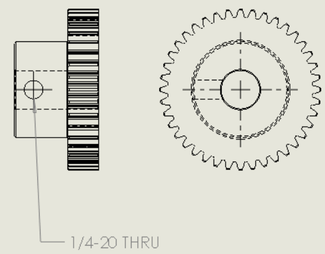

Notes:
Needed to add a hole for a set-screw to the gear so that it could be constrained to the axle.

ME 450 Team 24	
Project: Non-Propellor Propulsion System for Human Powered Submarine	
Ref Drawing: Gear40fullInput	
Engineer: Jonathan Kim	4/1/15
Proj. Mgr. Jonathan Meines	4/1/15
Sponsor: Allison Ward	4/1/15

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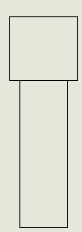

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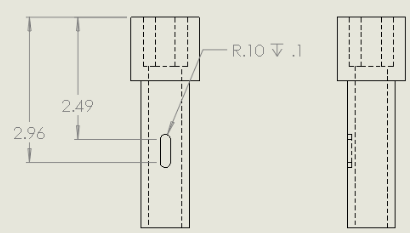

Notes:
Needed to add a slot so that the axle could be constrained to the gear with a key-way

ME 450 Team 24	
Project: Non-Propellor Propulsion System for Human Powered Submarine	
Ref Drawing: InputShaft	
Engineer: Jonathan Kim	4/1/15
Proj. Mgr. Jonathan Meines	4/1/15
Sponsor: Allison Ward	4/1/15

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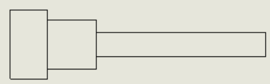

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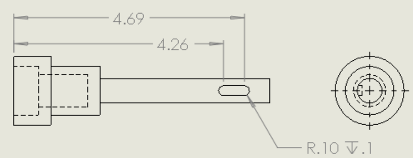

Notes:
Needed to add a slot so that the axle could be constrained to the gear with a key-way

ME 450 Team 24	
Project: Non-Propellor Propulsion System for Human Powered Submarine	
Ref Drawing: OutputShaft	
Engineer: Jonathan Kim	4/1/15
Proj. Mgr. Jonathan Meines	4/1/15
Sponsor: Allison Ward	4/1/15

5 4 3 2 1

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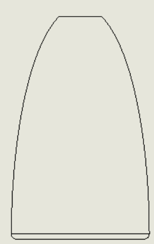

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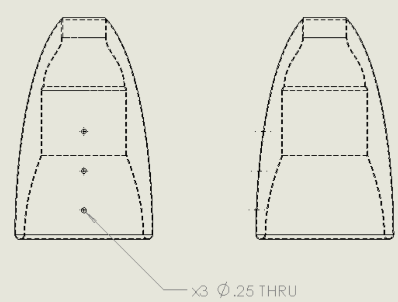


Notes:
Needed to add a slot so that the axle could be constrained to the gear with a key-way

ME 450 Team 24	
Project: Non-Propellor Propulsion System for Human Powered Submarine	
Ref Drawing: ImpellerDuctingCase3	
Engineer: Jonathan Kim	4/1/15
Proj. Mgr. Jonathan Meines	4/1/15
Sponsor: Allison Ward	4/1/15

5 4 3 2 1

APPENDIX D

Ethics

Jonathan Kim

It is important for every engineering to maintain high ethical standards, meaning that engineers must work with integrity and consider the safety of those in contact with the product. If these high standards are not kept, trust could be lost and people could be hurt or even killed.

We designed our system with the safety of the users in mind by giving it a substantial weight in our design Pugh chart. Since the water jet system keeps the moving impeller completely enclosed, the system is one of the safest designs for those in the water around the submarine as the system is in use. In comparison, a propeller or flapping wings can endanger anyone who comes close to them as they are in use. Safety, coupled with the high potential thrust efficiency, pushed the impeller design far ahead of the other designs in our Pugh chart.

In the design process, we were each given responsibility of an individual component of the system, but we constantly checked each other's progress and corrected mistakes we found. Also when an individual team member encountered a problem, the problem was shared with the rest of the team and we all helped to fix it. Furthermore, we were reviewed by other teams and professors throughout the years. We were open about the difficulties and shortcoming of our project and implemented the feedback we received. Constant communication was also kept with our client. We shared our design extensively with other engineers, so that mistakes could be found and dealt with instead of overlooked or ignored.

When machining the different parts of the system, we ensured that each team member used machines that the team member had adequate knowledge and experience on. Some of us were more experienced with the lathe, while one member had CNC mill training. We further supported each other in machining parts and came to each other for advice and help. This ensured that each member was machining safely.

Finally, we made design changes with the engineering design change. We turned in ECNs for the changes we made. This ensured that we did not make a change without anyone else's knowledge that could potentially be a hazard.

Our team strove to maintain high ethical standards throughout the entire engineering process. We knew that our own safety and the safety of those in contact of the product depended on our integrity and following of the code of ethics.

Jonathan Meines

We designed our product to be as safe as possible. The impeller module, in our Gantt chart, scored the highest possible in the safety category. The reason that the impeller module is so safe is because all of the moving parts are internal to the device; the gearbox is covered and the impeller is recessed within the ducting and stators. We designed only within the areas that we had knowledge and skills in or the ability to expand our knowledge and skills. An example of this is the design of the impeller. We didn't know how to design the actual geometries but we knew the fluid requirements, so we used CFturbo to fill the gap between what we knew and what we needed. As a team we acted professionally in our presentations and deliverables; which required us to employ our technical communication skills. Furthermore, in our presentations and deliverables we were honest in reporting our design, progress, and testing results. I believe that this design project has pushed us to become better engineers and will build a good reputation for us among our peers.

As a group we have not been involved in any bribery, fraud, or corruption. As a whole I believe that our group has upheld the engineering code of ethics.

Saketh Samaymantri

An important aspect of every design process is following the engineering code of ethics. It is essential that our team follow these guidelines and exhibit the highest standards of honesty and integrity. The safety of the public must be of high importance to every engineer. Our team has made sure to keep this in mind by incorporating safety as a highly important category in our Pugh chart when deciding on a solution to our problem. We made sure to design our impeller module to be as safe as possible to the user, and others that may be around it by completely enclosing all moving parts so that it does not harm anyone around it. Another code of ethics that engineers must follow is to only perform work that they are competent in. While many aspects of our impeller design were things that our team has had a lot of background in, such as gear ratios and fluid dynamics, we did not have the thorough background in actually designing the geometry of an impeller. In order to maintain our intellectual integrity, we used a trusted software called CFturbo to assist in designing the impeller. Additionally, we each only manufactured using machines that we had proper training in to ensure that our product was made as designed without any flaws, while also keeping in mind the safety of others working around us as well as ourselves. Our team also made sure to be completely truthful in all presentations and technical reports. If any issues arose, we were clear and honest about what the situation was and spoke with other engineers (peers, professors) about how to handle it, instead of ignoring it regardless of how minor the issue. We were also very transparent with our sponsors about every step of the process from initial brainstorming to validation testing, establishing ourselves as faithful and trusted engineers. Overall, I believe our team has effectively followed the Mechanical Engineering code of ethics.

Poalo Torres

As engineers, we gave every effort to design our project as much ethics as possible. We were each made responsible for whatever task was designated to us, while at the same time made sure it was a task that a group member can perform. We would keep each other as well as our instructors and sponsors up to date on progress, even if the progression was not at the point expected, and kept each other aware of any mistakes. If any of us had problems with completing a task, be it time or other circumstances, we would adjust our responsibilities accordingly. In every step of our process from the beginning of our project to our final design, it was important that the results we produce allows margin for error so that if problems with design arose, they would be easier to adapt to and that we could address them sooner rather than later. Due to the complexity of our design approach, we encountered plenty of unknowns, and it was important for us to explain these complexities. For the design stage, it was extremely important that our final design can still fulfill specifications without creating safety issues or compromising performance. For example, the gearbox is designed with a high safety factor because we feared that the gears inside might break. The gearbox will protect the internal components, and is made with a durable fiberglass composite. All our manufacturing was done with approved manufacturing plans, and performed safely. If any dimensions of the parts we were assigned to manufacture were even slightly off, we reported them and made sure it can easily be fixed or otherwise have minimal effect on design, assembly, and performance. Lastly, we will have our design validated with proper protocols and procedure that is well-thought out and well-explained. Throughout our project, we were transparent with every issue, honest in our conduct, and have complied with the engineering code of ethics to the best of our ability.

Environmental Impact

Poalo Torres

In designing our water jet module, we had to address the environmental impact of the module. Our finished product is designed to have a minimal environmental impact. It doesn't produce any kind of pollution or use any electricity, and all energy is human powered. It is made of materials such as stainless steel and aluminum all of which are corrosion-resistant and can be easily reused. The impeller is 3D printed, while the ducting and gearbox casing are made from molding a fiberglass composite into a tooling board mold, created with a CNC router. These methods produce a minimal amount of waste. The paint used is from Rust-Oleum, which is known to be compliant with VOC regulations. However, there were other factors considered, such as the manufacturing processes involved to get to the final product. For example, some of the parts I manufactured, such as the output axle and input shaft, cost more material and energy than I had hoped. The aluminum stock given to me was of a much larger diameter than the outer diameters of those parts, but it was the smallest that was readily available in the place my group member found it in. As a result, turning the stocks to shape on the lathe required more energy and produced plenty of aluminum scraps which I acknowledge was wasteful. Unfortunately, there was no other time-efficient method available to carve out a smaller diameter and still leave behind usable material. With regards to creating the ducting and gearbox casing, the CNC process to create the tooling board mold was a lengthy process, requiring a lot of energy to do so. With regards to the product's end of life, the ducting and gearbox casing are made of an epoxy-resin composite that can theoretically be recycled. However, because there are not any available outlets to do this, the composite will be landfilled. All other metal parts can be reused, recycled, or recast.

Jonathan Kim

The environmental impact of our system is overall minimal in that our design will not be mass produced or disposed of. Also our system is completely human powered, so most of the environmental impact is from manufacturing. After our system is no longer in use, it will be kept as a display model, so it will not have to be disposed.

The material for our project was chosen because of their corrosion resistant properties and strength. Our model is made up of aluminum, stainless steel, fiberglass composite, and chrome plated carbon steel. Our materials were either bought or given to us by the human powered submarine team's excess. Since only one of our system will ever be made, the impact of the making of the materials is minimal. We used the leftover materials that the human powered submarine team used. Also since our system is not made to be mass produced, the amount of energy needed to make it is also negligible.

Jonathan Meines

The materials that are present in our design include: aluminum, stainless steel, rubber, plastic, fiberglass, and epoxy. The environmental impact extends beyond just the materials present in the finished product. The environmental impact also includes all of the other materials, and the energy to required to make and transport the parts present in the finish product.

The composite parts have the greatest environmental impact per weight. To make the composite parts, a tooling board mold had to be cut on the router, painted, sanded, then vacuum bagged with the composite materials. The tooling board is a synthetic foam material requiring chemicals and energy to manufacture and then even more energy to cut on the cnc router. The painting process is done in a paint booth with a large fan, which extracts the volatile toxic fumes out of the booth. The lay-up process requires energy to run the vacuum pump and more synthetic materials such as the vacuum bag, release film, and bleeder cloth; all of which are discarded in the trash after each lay-up. After all of the parts are made the mold is discarded as well. Composite lay-up requires a lot of energy and many man-made materials; most of which cannot be recycled. The environmental impact of composite layup can be reduced by using the minimal amount of consumables necessary to still make the finished parts

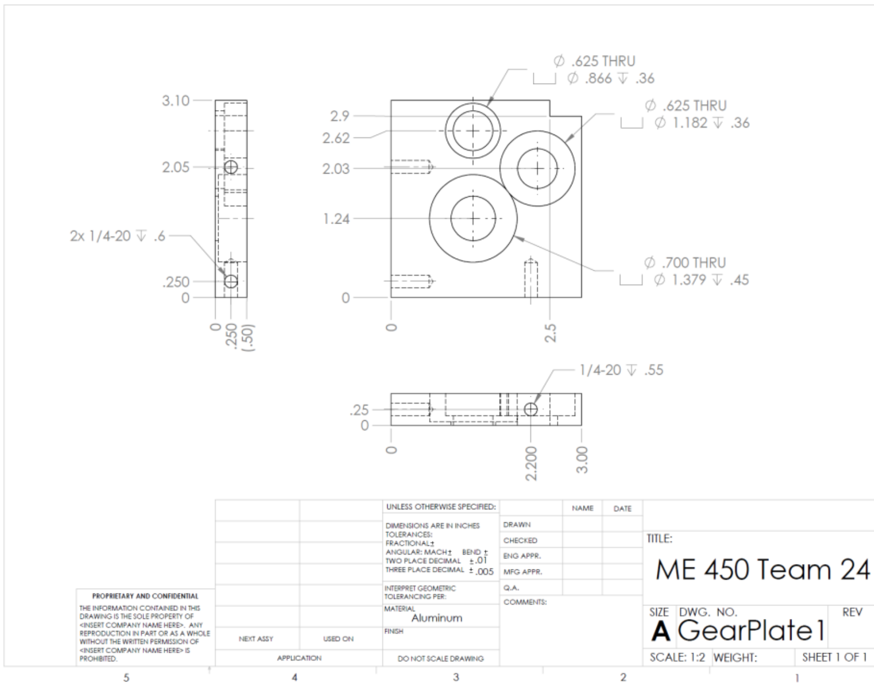
The metal parts, both custom and bought, will be reused, recycled, or discarded at the end of the product life-cycle, depending on the condition of the individual part. The composite parts will be discarded at the end of the product life-cycle as epoxy resin cannot be recycled.

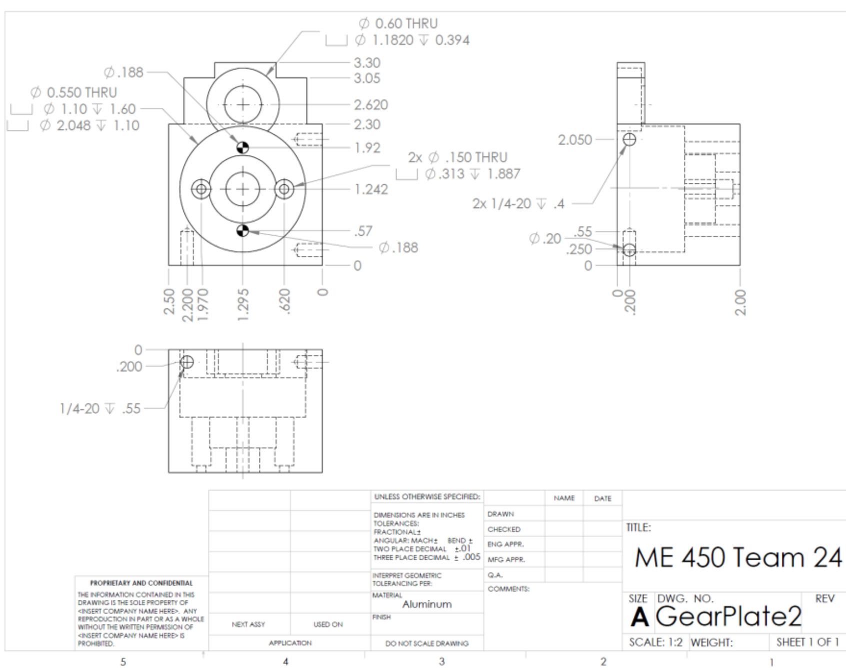
Saketh Samaymantri

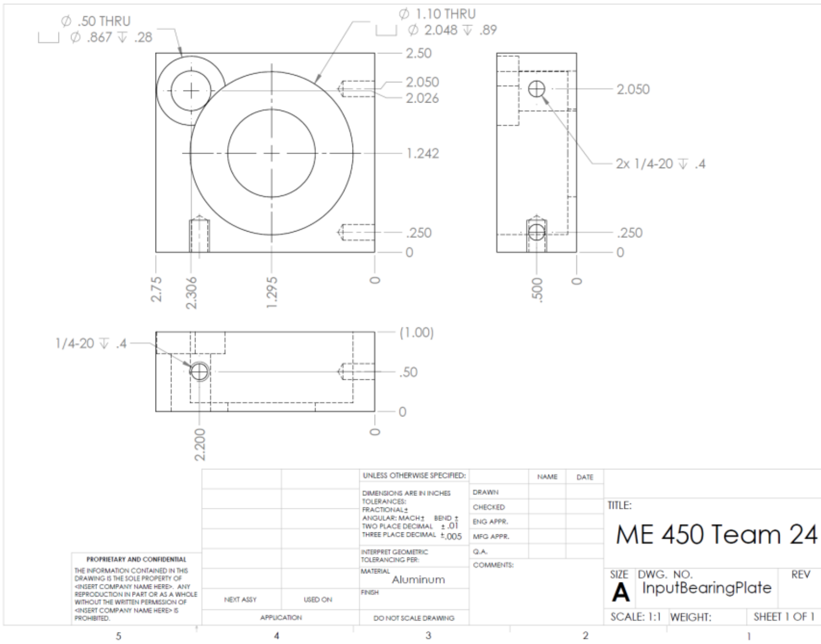
Our impeller module is made up of many different materials such as stainless steel, carbon steel, aluminum, plastic, and fiberglass. In machining various metal parts from the stainless steel and aluminum, a lot of the raw material is gone to waste on the cnc, mill and lathe. We also have to take into account the energy involved in running these machines for the duration of the manufacturing process. The fiberglass composite lay-up process has a much greater environmental impact than the metals since there is a lot more energy used and waste involved in that process. After our sponsor, the submarine team, is finished using our product, they will likely reuse some of the metal components, recycle what can be recycled, and throw out the remainder. The fiberglass components cannot be recycled so these parts will go to waste.

APPENDIX E

Drawings



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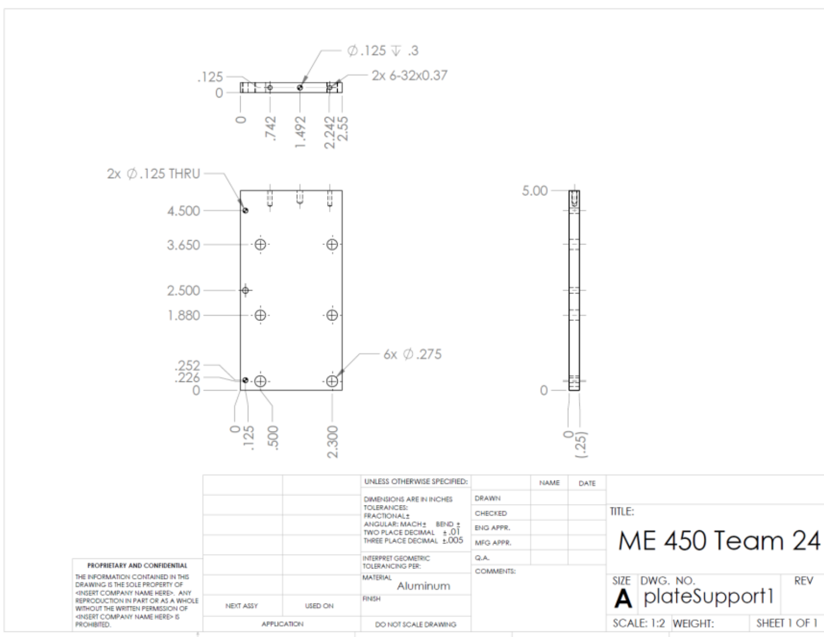
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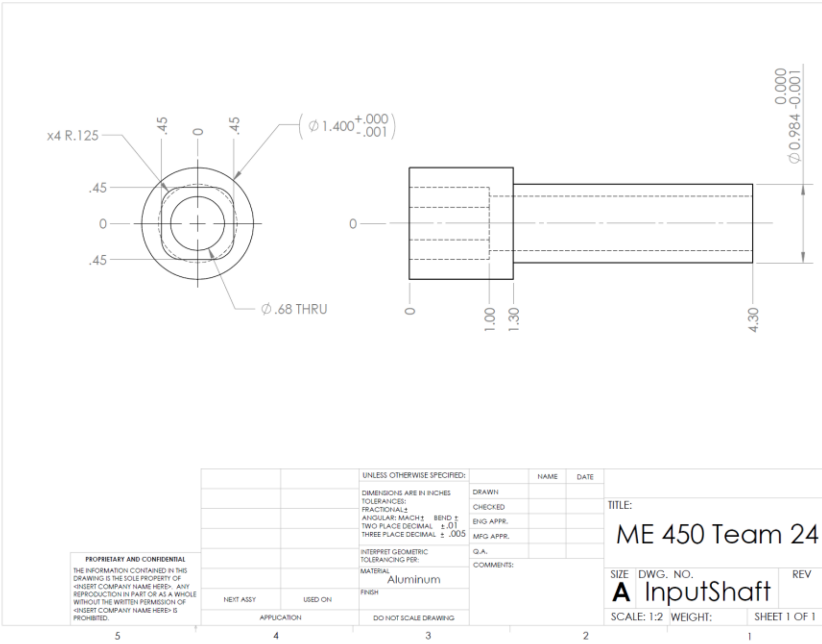
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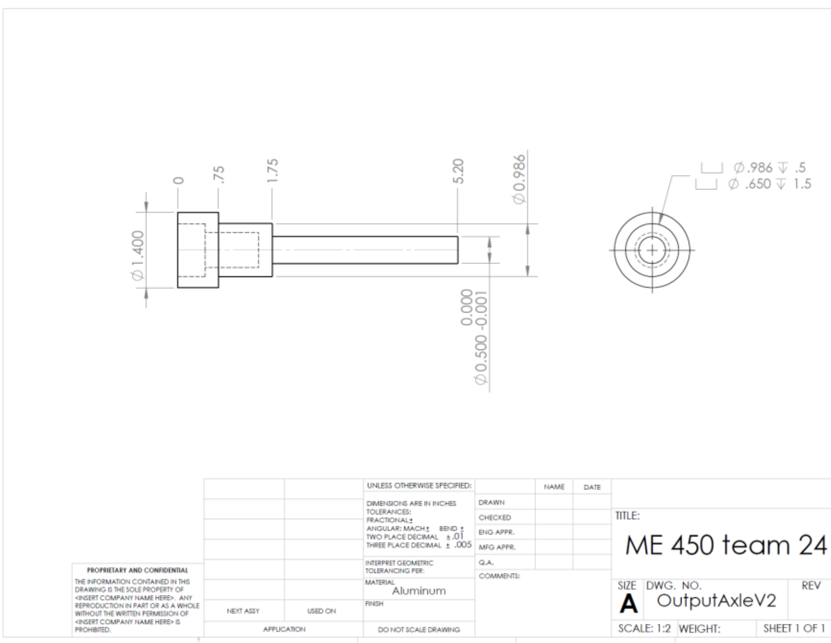
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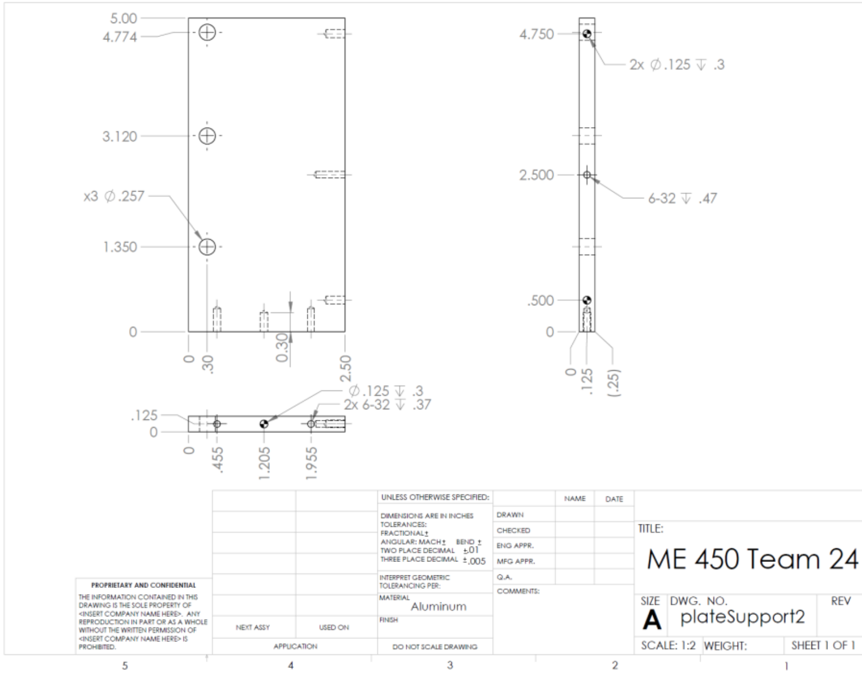
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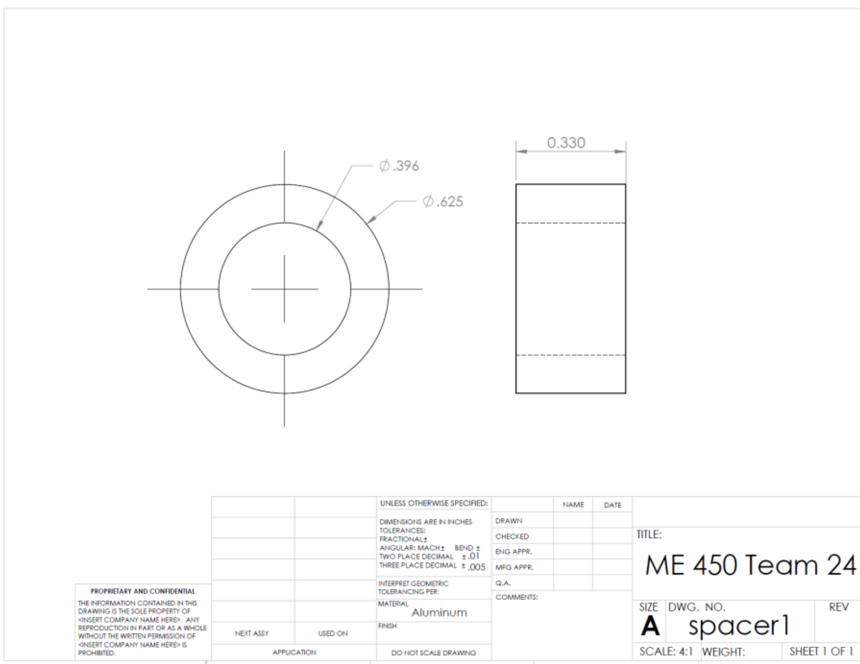
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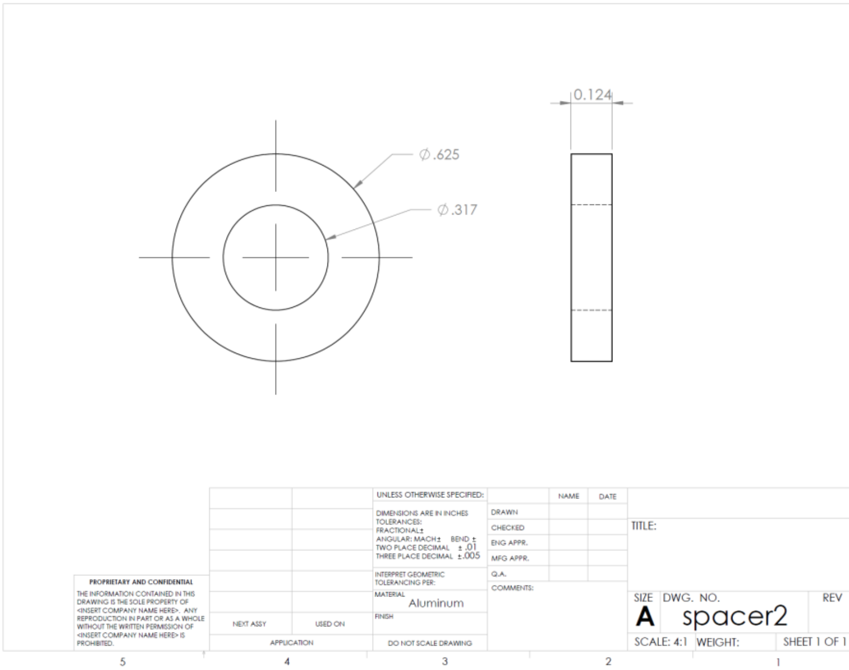
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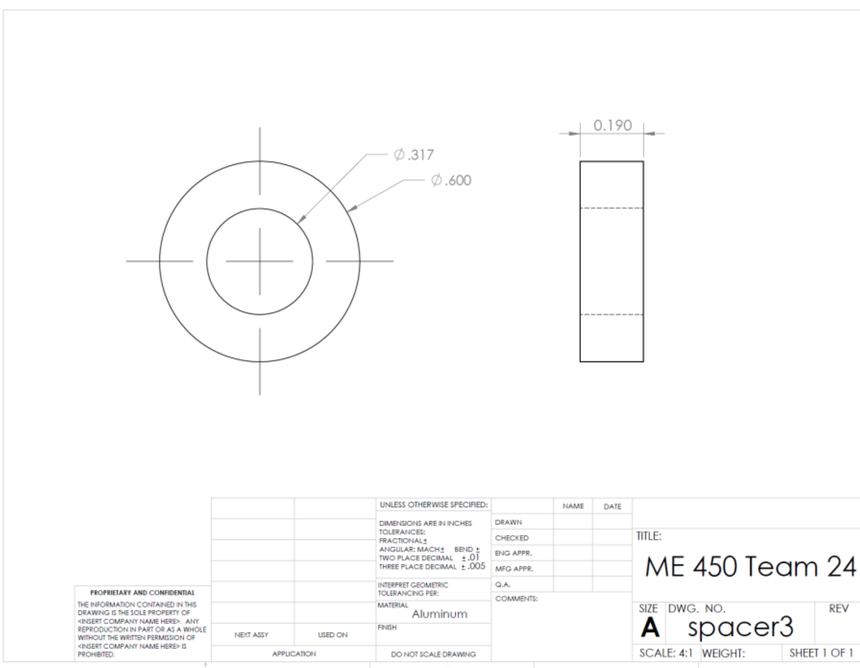
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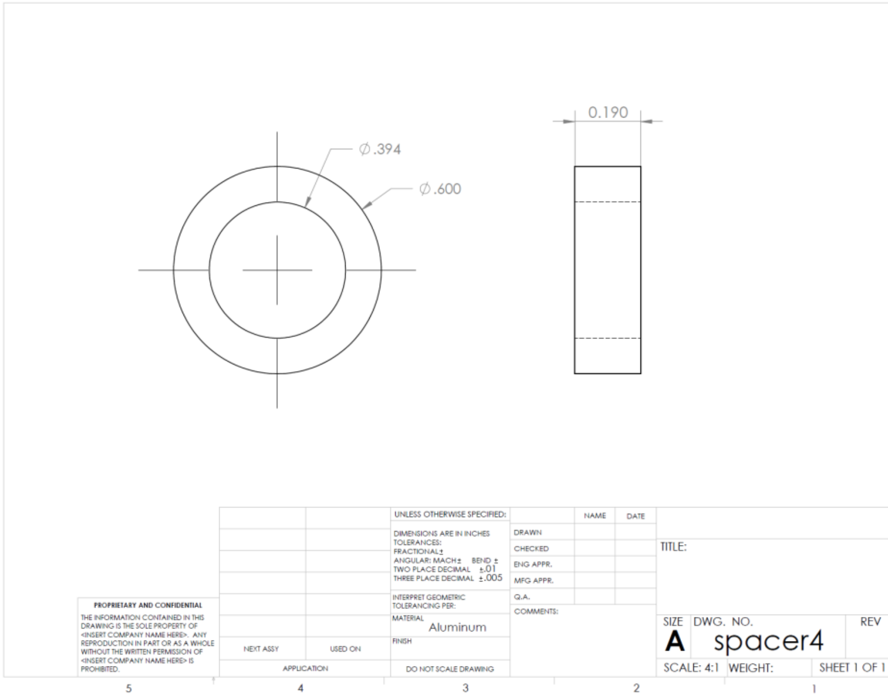
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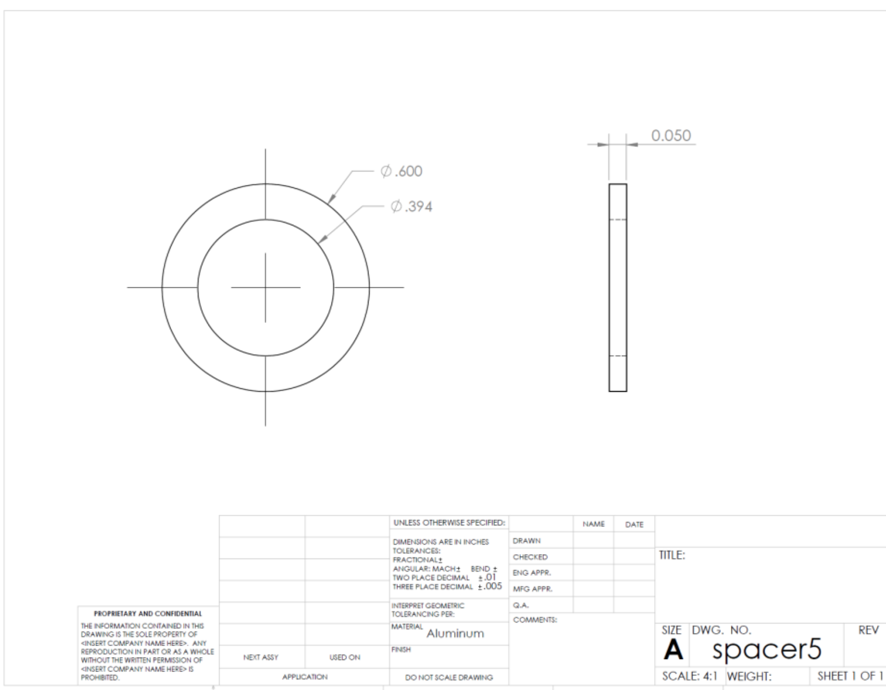
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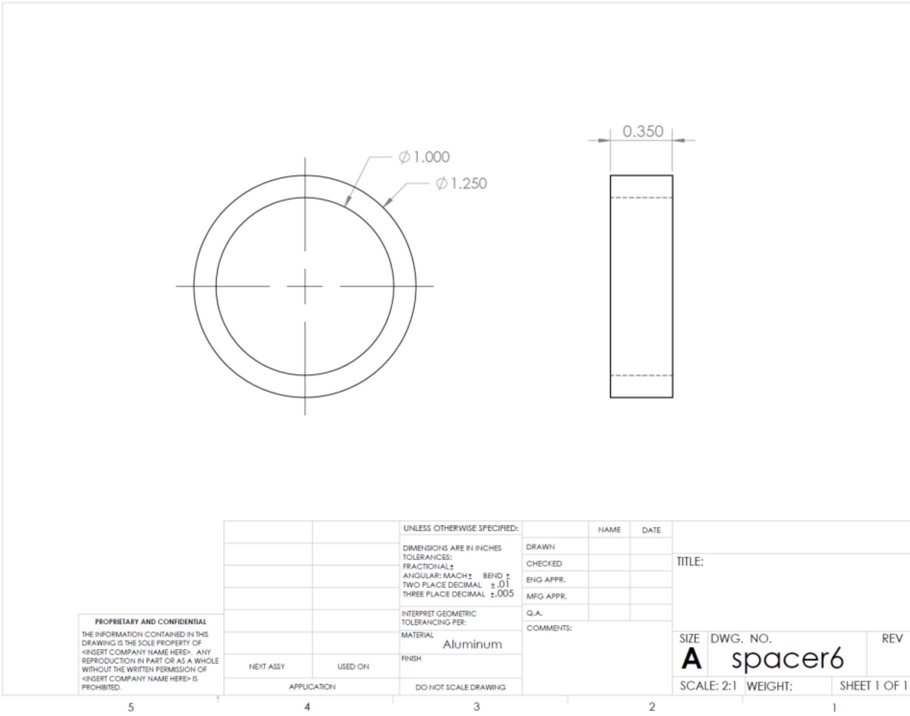
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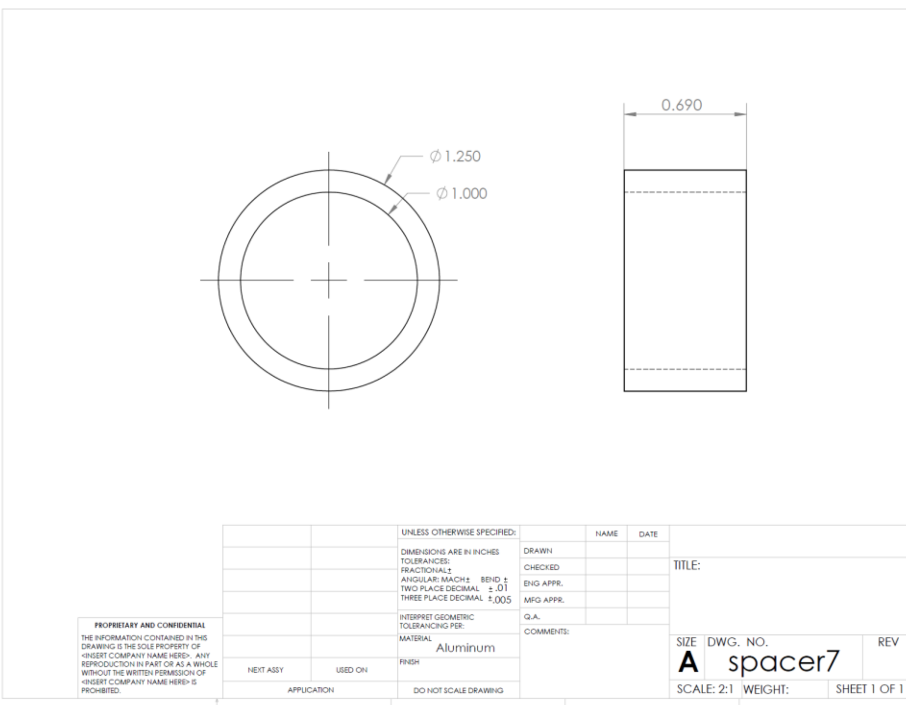
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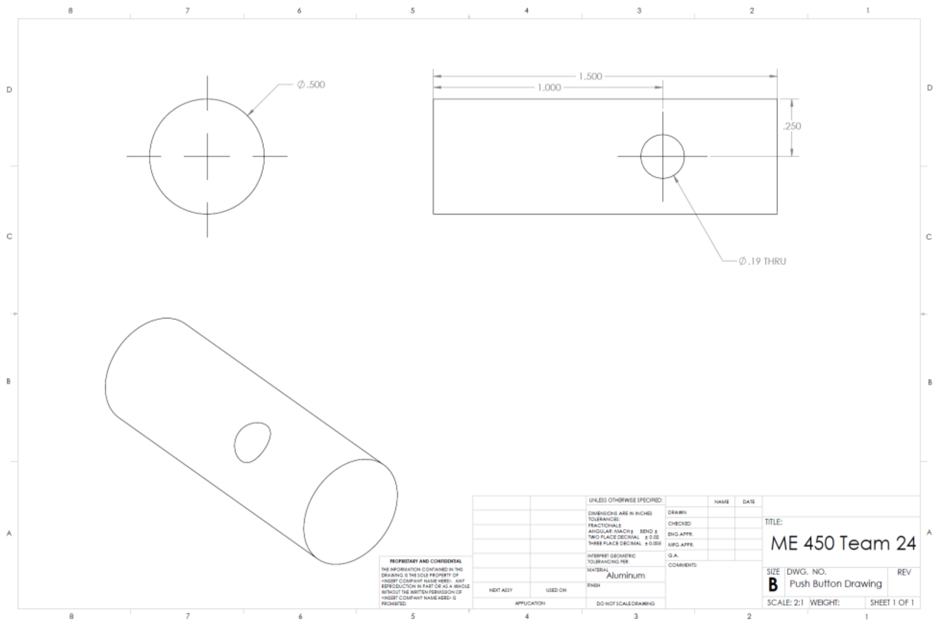
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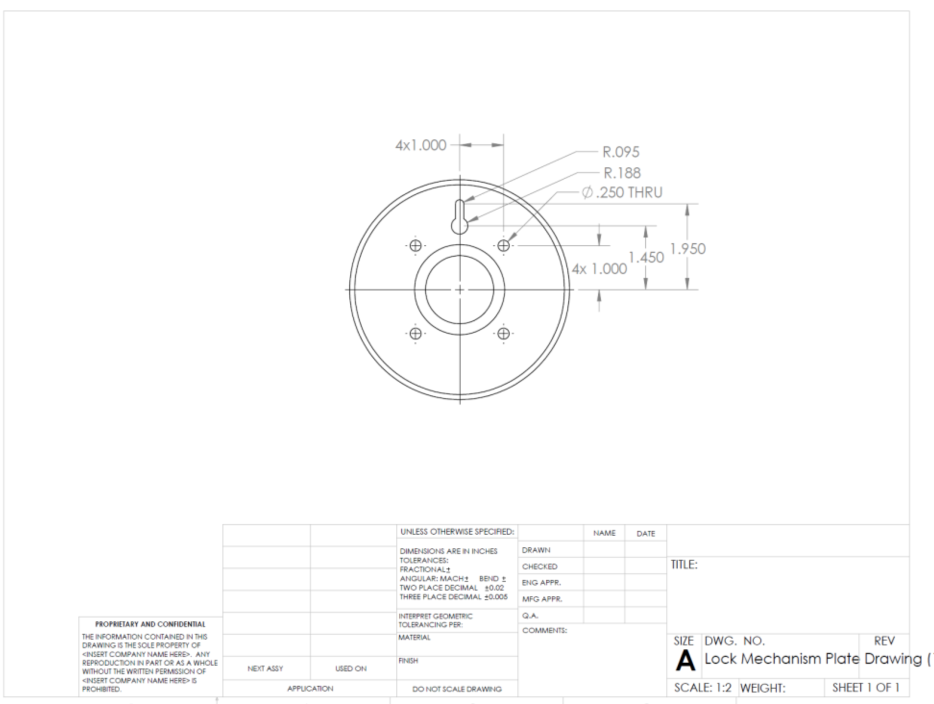
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APPENDIX F

Manufacturing Plans

Manufacturing Plan - GearPlate1

Material - Aluminum 1/2” Plate

	Details	Machine	Fixtures	Tool(s)	Speed
1.	Cut 1/2” aluminum plate to approximate size. 3.225” by 3.125”	Bandsaw			
2.	Hold part in vise.	Mill	vise	3/4” Parallels	
3.	Mill one end of part, just enough to provide fully machined surface. Along the shorter end.	Mill	vise	¾ inch 2-flute endmill, collet	500 RPM
4.	Mill opposite end of part to 3.10 length	Mill	vise	¾ inch 2-flute endmill, collet	500 RPM
5.	Mill adjacent end of part enough to provide fully machine surface	Mill	vise	¾ inch 2-flute endmill, collet	500 RPM
6.	Mill opposite end of part to 3.00 length	Mill	vise	¾ inch 2-flute endmill, collet	500 RPM
7	Mill out corner of the part	Mill	vise	¾ inch 2-flute endmill, collet	500 RPM
8.	Remove cutter and collet. Install drill chuck. Return part to vise.	Mill	vise	drill chuck	

9.	Find datum lines for X and Y	Mill	vise	edge finder, drill chuck	900 RPM
10.	Centerdrill and drill hole 0.63” holes.	Mill	vise	Center drill, 5/8” drill bit	600 RPM
11.	Centerdrill and drill hole for 0.70” hole	Mill	vise	Center drill, 45/64” drill bit	350 RPM
12.	Remove and find datum lines for X and Y. This is for the ¼-20 holes.	Mill	vise	edge finder, drill chuck	900 RPM
13.	Centerdrill and drill hole for ¼-20	Mill	vise	Center drill, #7 drill bit	1200 RPM
14.	Repeat steps 12 and 13 for other ¼-20 holes				
15.	Tap the ¼-20 hole by hand, using the center to align the other end of the tap	Mill	vise	Center, drill chuck/ ¼-20 tap and handle	

Manufacturing Plan - GearPlate2

Material - Aluminum 2” Plate

	Details	**Machine**	**Fixtures**	**Tool(s)**	**Speed**
1.	Cut 2” aluminum plate to approximate size. 2.625” by 3.425”	Bandsaw			
2.	Hold part in vise.	Mill	vise	1/2” Parallels	
3.	Mill one end of part, just enough to provide fully machined surface. Along the shorter end.	Mill	vise	1 inch 2-flute endmill, collet	400 RPM

4.	Mill opposite end of part to 3.10 length	Mill	vise	1 inch 2-flute endmill, collet	400 RPM
5.	Mill adjacent end of part enough to provide fully machine surface	Mill	vise	1 inch 2-flute endmill, collet	400 RPM
6.	Mill opposite end of part to 3.00 length	Mill	vise	1 inch 2-flute endmill, collet	400 RPM
7	Mill contour on the top of the part	Mill	vise	1 inch 2-flute endmill, collet	400 RPM
8.	Remove cutter and collet. Install drill chuck. Return part to vise.	Mill	vise	drill chuck	
9.	Find datum lines for X and Y	Mill	vise	edge finder, drill chuck	900 RPM
10.	Centerdrill and drill hole 0.63” holes.	Mill	vise	Center drill, 5/8” drill bit	400 RPM
11.	Centerdrill and drill hole for 0.70” hole	Mill	vise	Center drill, 45/64” drill bit	350 RPM
12.	Remove and find datum lines for X and Y. This is for the ¼-20 holes.	Mill	vise	edge finder, drill chuck	900 RPM
13.	Centerdrill and drill hole for ¼-20	Mill	vise	Center drill, #7 drill bit	1200 RPM
14.	Repeat steps 12 and 13 for other ¼-20 holes				

15.	Tap the ¼-20 hole by hand, using the center to align the other end of the tap	Mill	vise	Center, drill chuck/ ¼-20 tap and handle	

Manufacturing Plan - Input Bearing Plate

Material - Aluminum 1” Plate

	Details	**Machine**	**Fixtures**	**Tool(s)**	**Speed**
1.	Cut 1” aluminum plate to approximate size. 2.875” by 2.625”	Bandsaw			
2.	Hold part in vise.	Mill	vise	½” Parallels	
3.	Mill one end of part, just enough to provide fully machined surface. Along the shorter end.	Mill	vise	¾ inch 2-flute endmill, collet	500 RPM
4.	Mill opposite end of part to 2.75 length	Mill	vise	¾ inch 2-flute endmill, collet	500 RPM
5.	Mill adjacent end of part enough to provide fully machine surface	Mill	vise	¾ inch 2-flute endmill, collet	500 RPM
6.	Mill opposite end of part to 2.50 length	Mill	vise	¾ inch 2-flute endmill, collet	500 RPM
7.	Remove cutter and collet. Install drill chuck. Return part to vise.	Mill	vise	drill chuck	
8.	Find datum lines for X and Y	Mill	vise	edge finder, drill chuck	900 RPM

9.	Centerdrill and drill hole 0.50" hole.	Mill	vise	Center drill, ½" drill bit	600 RPM
10.	Centerdrill and drill hole for 1.10" hole	Mill	vise	Center drill,	
11.	Remove and find datum lines for X and Y. This is for the ¼-20 holes.	Mill	vise	edge finder, drill chuck	900 RPM
12.	Centerdrill and drill hole for ¼-20	Mill	vise	Center drill, #7 drill bit	1200 RPM
13.	Repeat steps 11 and 12 for other ¼-20 holes				
14.	Tap the ¼-20 hole by hand, using the center to align the other end of the tap	Mill	vise	Center, drill chuck/ ¼-20 tap and handle	

Manufacturing Plan - Input Shaft

Material - 1 1/2 " Round Stock

	Details	**Machine**	**Fixtures**	**Tool(s)**	**Speed**
1.	Face end and turn larger OD	Lathe		Turning tool	500 RPM
2.	Part the part	Lathe		Parting tool	120 RPM
3.	Turn smaller OD	Lathe		Turning tool	630 RPM
4.	Center drill for through hole	Lathe		#3 Center drill	1000 RPM
5.	Drill through hole	Lathe		¼" Drill	1000

				Bit	RPM
6.	Drill final ID through hole	Lathe		0.68 Drill Bit	400 RPM
7.	Pocket out the square blind hole	Mill	V-blocks, Vice	¼” endmill	1200 RPM

Manufacturing Plan - OutputAxleV2

Material - 1 ½ “ Round Stock

	Details	**Machine**	**Fixtures**	**Tool(s)**	**Speed**
1.	Face end and turn smallest two OD’s	Lathe		Facing tool	630 RPM
2.	Flip part and turn largest OD	Lathe		Facing tool	630 RPM
3.	Center drill for blind holes	Lathe		#3 center drill, chuck	800 RPM
4.	Drill 0.5 blind hole	Lathe		0.5 Drill, chuck	500 RPM
5.	Bore out the stepped blind hole using the previous hole as a starting point	Lathe		Boring bar	630 RPM

Manufacturing Plan - plateSupport1

Material - Aluminum 1/4” Plate

	Details	**Machine**	**Fixtures**	**Tool(s)**	**Speed**

1.	Cut 1/4” aluminum plate to approximate size. 2.68” by 5.13”	Bandsaw			
2.	Hold part in vise.	Mill	vise	3/4” Parallels	
3.	Mill one end of part, just enough to provide fully machined surface. Along the longer end.	Mill	vise	1/2 inch 2-flute endmill, collet	800 RPM
4.	Mill opposite end of part to 2.55 length	Mill	vise	1/2 inch 2-flute endmill, collet	800 RPM
5.	Mill adjacent end of part enough to provide fully machine surface	Mill	vise	1/2 inch 2-flute endmill, collet	800 RPM
6.	Mill opposite end of part to 5.00 length	Mill	vise	1/2 inch 2-flute endmill, collet	800 RPM
7.	Remove cutter and collet. Install drill chuck. Return part to vise.	Mill	vise	drill chuck	
8.	Find datum lines for X and Y	Mill	vise	edge finder, drill chuck	900 RPM
9.	Centerdrill and drill hole .275” holes.	Mill	vise	Center drill, J drill bit	1300 RPM
10.	Centerdrill and drill hole for 0.125” holes	Mill	vise	Center drill, #31 drill bit	1800 RPM
11.	Ream 0.125” holes	Mill	vise	⅛” reamer	200 RPM

12.	Centerdrill and drill hole for 0.144" holes	Mill	vise	Center drill, #27 drill bit	1500 RPM
13.	Remove and find datum lines for X and Y.	Mill	vise	edge finder, drill chuck	900 RPM
14.	Centerdrill and drill hole for 6-32 holes	Mill	vise	Center drill, #36 drill bit	1600 RPM
15.	Centerdrill and drill hole for .125" hole	Mill	vise	Center drill #31 dril bit	1800 RPM
16.	Ream 0.125" holes	Mill	vise	⅛" reamer	200 RPM
17.	Tap the 6-32 hole by hand, using the center to align the other end of the tap	Mill	vise	Center, drill chuck, 6-32 tap and handle	

Manufacturing Plan - plateSupport2

Material - Aluminum 1/4" Plate

	Details	**Machine**	**Fixtures**	**Tool(s)**	**Speed**
1.	Cut 1/4" aluminum plate to approximate size. 2.68" by 5.13"	Bandsaw			
2.	Hold part in vise.	Mill	vise	3/4" Parallels	
3.	Mill one end of part, just enough to provide fully machined surface. Along the longer end.	Mill	vise	1/2 inch 2-flute endmill, collet	800 RPM
4.	Mill opposite end of part to 2.55 length	Mill	vise	1/2 inch 2-flute	800

				endmill, collet	RPM
5.	Mill adjacent end of part enough to provide fully machine surface	Mill	vise	1/2 inch 2-flute endmill, collet	800 RPM
6.	Mill opposite end of part to 5.00 length	Mill	vise	1/2 inch 2-flute endmill, collet	800 RPM
7.	Remove cutter and collet. Install drill chuck. Return part to vise.	Mill	vise	drill chuck	
8.	Find datum lines for X and Y	Mill	vise	edge finder, drill chuck	900 RPM
9.	Centerdrill and drill hole .275” holes.	Mill	vise	Center drill, J drill bit	1300 RPM
10.	Remove and find datum lines for X and Y.	Mill	vise	edge finder, drill chuck	900 RPM
11.	Centerdrill and drill hole for 6-32 holes	Mill	vise	Center drill, #36 drill bit	1600 RPM
12.	Centerdrill and drill hole for .125” hole	Mill	vise	Center drill #31 dril bit	1800 RPM
13.	Ream 0.125” holes	Mill	vise	⅛” reamer	200 RPM
14.	Repeat steps 10-13 for other side				
15.	Tap the 6-32 hole by hand, using the center to align the other end of the tap	Mill	vise	Center, drill chuck, 6-32 tap and handle	

Manufacturing Plan - (Ducting and Cowling)

Material - Existing Plate

	Details	Machine	Fixtures	Tool(s)	Speed
1.	Tool the mold cavities	CNC Router		½" ball endmill	17K
2.	Sand the molds	downdraft tables		sandpaper	
3.	Paint the molds	Paint booth		dump gun	
4.	Sand the molds to a mirror finish	downdraft tables		sandpaper	
5.	Cut fiberglass to size			scissors	
6.	Lay-up of composites	vacuum pump			

Manufacturing Plan - (Impeller and Cone)

Material - Existing Plate

	Details	Machine	Fixtures	Tool(s)	Speed
1.	Send STL files to Burton Precision	Internet		Laptop	Light
2.	Burton 3D prints the parts	SLA printer			not fast
3.	Burton sends us the parts	USPS			slow

Manufacturing Plan - (Impeller Shroud)

Material - Existing Plate

	Details	Machine	Fixtures	Tool(s)	Speed
1.	Cut the stock to size	Horizontal bandsaw			
2.	Turn the OD	Lathe		Turning/facin g cutter	500 RPM
3.	Turn the ID	Lathe		Boring Bar	630 RPm
4.	Machine the stators	CNC mill (Haas)	rotary vice	¼” carbide ball endmill	7000 RPM

Manufacturing Plan - (Mounting Lock Plate)

Material - Existing Plate

	Details	Machine	Fixtures	Tool(s)	Speed
1.	Mark 4 dowel pin holes 1 inch above/below and left/right of the center of the plate			calipers	
2.	Center Drill 4 .250” holes	Mill	Vice		
3.	Ream holes to .251”	Mill	Vice		
4.	Mark center of screw head hole 1.450” above center of plate			calipers	
5.	Mark center of screw shaft hole 1.950” above center of plate			calipers	
6.	Drill .157” radius hole 1.450” above center of plate	Mill	Vice		

7.	Drill .095” radius slot from 1.950” above center of plate to 1.450” above center of plate	Mill	Vice		

Manufacturing Plan - Push Button Rod

Material - 0.5" Diameter 6061 Aluminum Rod

	Details	**Machine**	**Fixtures**	**Tool(s)**	**Speed**
1.	Mark 2.25” on aluminum rod			calipers	
2.	Cut 2.25” from aluminum rod	Band saw	Wooden Block		1000 ft/min
3.	Mark 2” on aluminum rod			calipers	
4.	Refine aluminum rod to 2”	Mill	Vice		3600 rpm
5.	Mark out screw hole 1.3” from end in center of rod			calipers	
6.	Center drill screw holes	Mill	vice	Center Drill	3600 rpm
7.	Drill .19” diameter holes	Mill	vice	Clearance Hole Drill (H)	3600 rpm