Low Cost Submersible Thruster

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Date: _____

Low Cost Submersible Thruster Final Project Report

Sponsored By:

SPAWAR
Systems Center
PACIFIC

ADVANCED
MOTION CONTROLS

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CAL POLY

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Introduction

The objective of this project is to design and build a disposable underwater thruster. This thruster will have an operational life of a few hours, much shorter than the industry standard operating life that spans multiple years. While maintaining reliability as a priority, our goal is to significantly reduce the cost of our thruster compared to other thrusters on the market today.

Our stakeholders are the Space and Naval Warfare Systems Center Pacific (SPAWAR SYS CEN PAC), a technical center that provides research, development, communications, and logistic support to the US Navy. The US Navy currently has a disposable vehicle that uses two Tecnadyne Model 1060 thrusters worth a total of $17000. These thrusters are common off-the-shelf and designed for years of use. The current thrusters are used to reduce the speed of the system as it descends to the ocean floor and then transport the system to a desired location. The vehicle itself has a service life of just a few hours, making the thrusters a significant sunk cost for the system. Reducing the cost of these thrusters to less than $3000 each would represent a potential cost savings of more than $10000 per vehicle, making this project a worthwhile endeavor for our stakeholders. The Navy is estimating <100 full systems being manufactured, in which each system will require two thrusters. In terms of the Navy's current project, there will be a limited number of thrusters built, however several other projects require disposable thrusters in which our project can be utilized in future applications. While the Navy's requirements for service life are far lower for this particular vehicle, high reliability and performance are still critical. We will have to design our thrusters around this unique set of parameters, reducing the unit cost as much as possible.

Background

The current Remotely Operated Vehicle (ROV) thruster market is divided into two main subgroups: hydraulic drive and electric drive. Hydraulic systems tend to excel in high torque, low speed applications whereas electric systems tend to be implemented in high speed, low-medium torque applications.

Hydraulic systems are implemented in applications where size is a key design factor. These systems have high thrust to size ratio at the shaft because the large components (pump and hydraulic fluid reservoir) can be installed where size isn't a constraint and provide the small hydraulic motors with pressure. Additionally, in situations where the load could stall the motor, hydraulic systems stop without suffering any damage whereas electric motors may burn out and suffer permanent damage from stalling.

Underwater hydraulic systems have four main components: pump, reservoir, control block and motors. Most systems run using a constant pressure pump and use an electrohydraulic control system to distribute pressure to various subsystems. Like every other deep sea system, hydraulic systems must cope with increasing static pressures at depth. However, by implementing a simple system in which the reservoir is exposed to the ocean through a flexible membrane, the system is

compensated for the increasing static pressures at depth. To further simplify the system, the motor and pump can be submerged in the hydraulic fluid reservoir. This eliminates the need for any complicated motor seals and helps cool the motor. A simple schematic of the system is show in Figure 1 below.

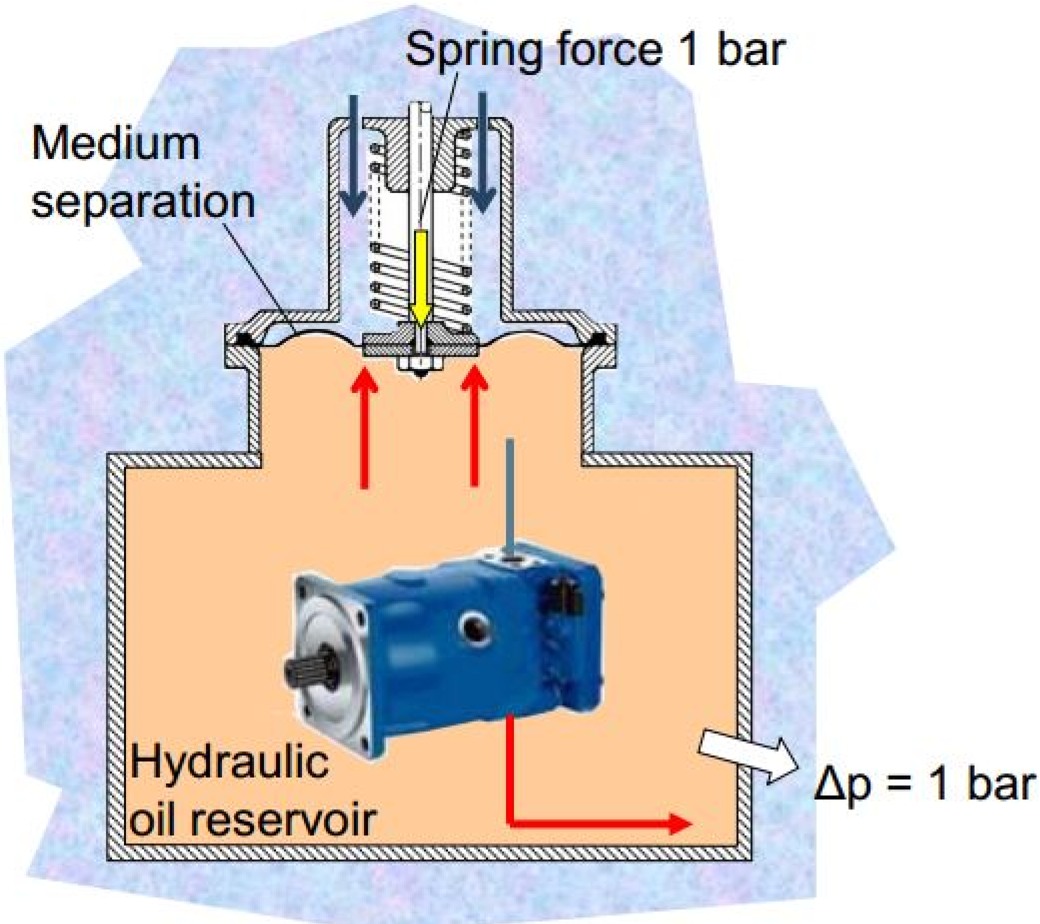


Figure 1 Hydraulic Oil Reservoir with embedded pressure compensator and pump to eliminate the need for advanced shaft seals on the pump motor [1].

To control the various subsystems, the pressure is distributed using a system of hydroelectric valves. This control block must either be kept fully sealed or pressure compensated depending on depth requirements. This system complicates the control system substantially. Not only does the controller need to control flow speeds, but also control fluid distribution after the pump to control individual thruster speed. For a single use application, a solenoid rack as shown below in Figure 2 won't be as cost effective as the hydraulic system. While this system would be more reliable, long term reliability isn't a necessity for this project. [1]

Figure 2 Solenoid valve control block for oil distribution to subsystems.

Conversely, the main attractions of electric motors are their lower cost, higher efficiency, and wide variety. Direct drive systems are substantially more efficient than hydraulic systems, which suffer from pumping losses. Most small thrusters run at high speed, making an electrically driven system attractive. With an oil-filled pressure compensated housing, an electric thruster no longer requires advanced, expensive seals.

Alternative Energy Source

Another point of cost savings for our group would be an alternative energy source. At the moment the electric thrusters are powered with a battery pack. Batteries are a highly attractive energy storage device if you are looking for reusable applications. Since this system will be deployed once and is not intended to be retrieved the 20,000 dollar cost for batteries is significant. Three possibilities that were researched were closed cycle diesel engines or a chemical reaction which would be harnessed either in a turbine and generator or directly through a pneumatic motor. While the closed cycle diesel engine would be a huge cost saver, it would require too much space to store all of the O2 needed to run the engine. Small diesel engines are also unreliable in terms of shelf life. With a required shelf life of five years, we do not have confidence that the engine would start every time after sitting with fuel in the lines. Additionally, putting a fuel port to fill the tank from the outside of the pressure vessel brings in a lot of complications.

The next alternative was sending steam created through a chemical reaction through a pneumatic motor. This was quickly ruled out due to the fact that most pneumatic motors are no more than 30-40% efficient. [2] The volumetric flow rate of steam to operate a suitable pneumatic motor was way out of scale.

The chemical reaction studied was hydrogen peroxide as the fuel with silver as the catalyst. To get the necessary volumetric expansion from this reaction, the hydrogen peroxide would need to be above 65% pure. At 85% pure there is a 4500 expansion multiplier from the reaction. This reaction also burns at 600°C?. [3] This same reaction was used for the last alternative energy source, sending the steam through a turbine. The specific turbine analyzed was a Tesla Turbine. Theoretically, these turbines can run at 98% efficiency. [4] For practical purposes, we stated that an efficiency of 60% was attainable. As with the diesel engine, we were unable to meet our volumetric requirements with this system. Although significantly cheaper, there are issues with both space and reliability. After an analysis of alternatives (AoA) it was decided that the best way to proceed is to stick with an electric thruster powered solely by batteries.

For our project, we are interested in creating a low cost thruster to be utilized for a short period of time with high reliability. Many of the existing models of thrusters present in the market are designed for a long life and are costly to manufacture. Currently SPAWAR is using two Tecnadyne 1060 thrusters that cost $8500 each, with specifications presented in Figure 3. These thrusters are rated for 105 lbf of forward thrust and require 2.7 kW at maximum thrust. This model uses magnetic couplings to power the propeller to negate the possibility of a leak through a rotary shaft seal. These thrusters are efficient and rated for a long run life, however are not ideal for our application.

TECNADYNE

MODEL 1060

DC BRUSHLESS THRUSTER

- 2.7kw thruster develops over 105lbf (48 kgf) forward thrust & over 65lbf (29.5kgf) reverse thrust.
- Powerful direct drive DC brushless motors for low noise in noise sensitive applications.
- Magnetically coupled propeller drive eliminates all rotating shaft seals for optimum reliability.
- Custom designed high efficiency propeller & Kort nozzle for maximum Bollard thrust.
- Investment cast Type 316 stainless steel propeller is available in both RH and LH rotation.
- Available with +/-5v analog or RS485 closed loop speed control.
- Rated to 2,800 ft (850m) or optional 5,000 ft (1,500m) depth with 1 atmosphere housings or full ocean depth with oil filled, pressure balanced housings.
- Available with hard anodized 6061-T6 aluminum, Type 316 stainless steel or 6Al4V titanium housings.
- Available with motors for 72vdc, 100vdc, 120vdc, 150vdc, 260vdc or 300vdc. Other voltages optional.

Bollard Output	***Input***	***Weight***	***Depth Rating***
105lbf (48kgf) forward, 65lbf (29.5kgf) reverse, w/ either RH or LH stainless steel propellers.	2.7kw at 72vdc, 100vdc, 120vdc, 150vdc, 260vdc or 300vdc, +/-5v analog or RS485 speed control.	12-17.5lbs (5.5-8kg) in air, 9-13lbs (4-6kg) in water, depending on configuration.	2,800ft (850m) & 5,000ft (1,500m) with 1 atm housings, full ocean depth when oil filled (PBOF). (specifications subject to change without notice)

03/25/14 1

Figure 3 Technadyne 1060 thruster (current model used on system) [5]

Benefits of a shrouded propeller

According to our sponsor, the vehicle for which these thrusters are designed operates at maximum speed of one knot. Propellers are inherently inefficient at low speeds. It has been observed as early as 1935 that shrouding a propeller with a nozzle "add[s] considerably to effective thrust at speeds below four miles per hour, providing quicker acceleration." [6] Several different airfoil types have been developed in the past to provide different characteristics under

certain circumstances. For example, the Kort 19a nozzle is a very common nozzle used in tug boats because it provides substantial increases in thrust at low speeds. In addition, at low speeds, the airfoil shape of the nozzle provides positive thrust in the direction of travel as shown in Figure 4 below [7]. The total lift vector of the airfoil is denoted dL and the forward component of the lift is denoted dT. Observe the direction of the airfoil thrust vector is in the same direction as the motion of the vessel.

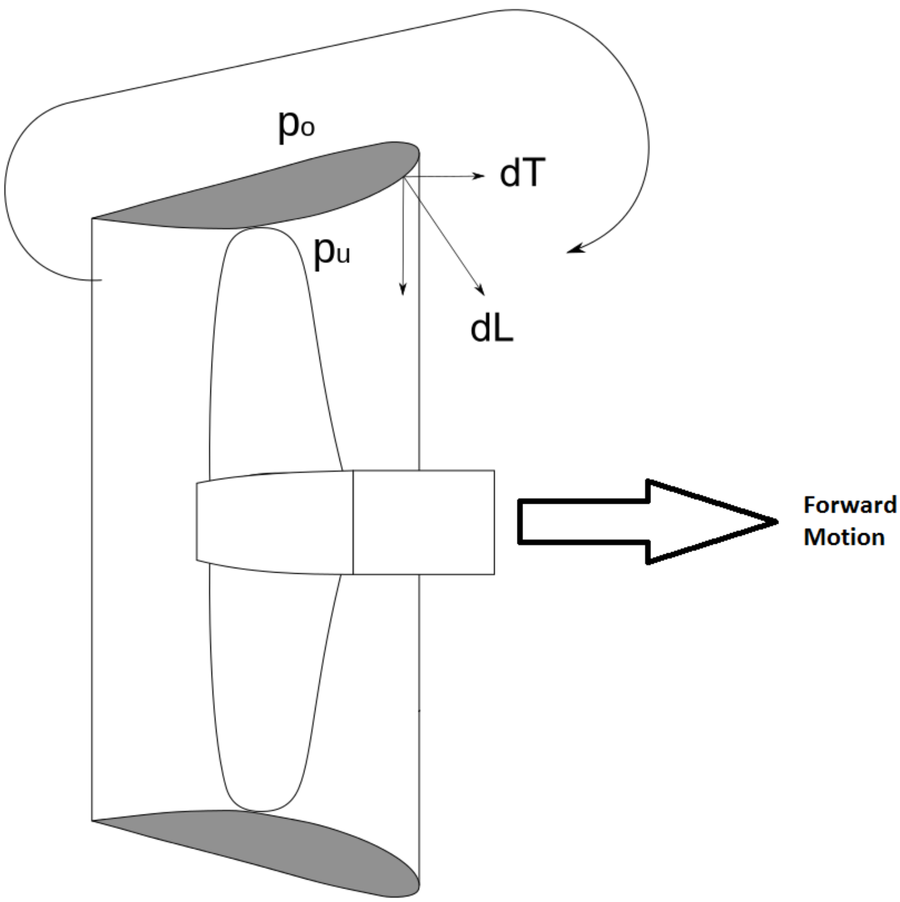


Figure 4 Thrust generated by a Kort 19a nozzle at low hull speed [7]

Unlike most vessels which need a thruster to provide both forward and reverse thrust, the vehicle for which these thrusters are designed for allows the thruster assembly to function as an azimuth pod meaning the thruster rotates a full 360°. The thruster assembly was therefore designed for forward thrust and when reverse thrust is needed, the pod rotates 180°. The abovementioned Kort 19a nozzle is designed specifically for unidirectional thrust. Implementing such a nozzle was vital to maximizing thrust.

Basic propeller design approach

Propeller design is an extremely complicated process. We have chosen diameter and thrust to be the driving parameters in our design process. Thrust is directly related to effective blade area. In

order to increase the blade area for a given diameter, the designer must increase the number of blades. However, shrinking the distance between blades decreases the propeller's efficiency because each blade experiences more turbulence generated by other nearby blades. Therefore, a two bladed propeller is the most efficient, but would need to have a larger diameter to have equal blade area of a three or four bladed propeller. Higher blade numbers also decreases the loading on individual blades, reducing vibration and stress on each blade. [8]

To model and optimize our propeller design, we used OpenProp, an open source Matlab script written by MIT and Dartmouth graduate students. OpenProp uses moderately loaded lifting line theory to model propeller behavior. The code optimizes a propeller given a set of input conditions and shroud geometries. It can solve both a single and a parametric array of inputs to generate the most efficient propeller. We have begun modeling propellers already and are experimenting with different blade geometries and shroud geometries. In addition, OpenProp allows us to export geometries into SolidWorks to further develop the hub. Figure 5 below is an exported 3D Matlab model generated by OpenProp for our application. Additionally, OpenProp can be customized to generate models which can easily be 3D printed and have the structural integrity to handle testing. Validating the theoretical model with empirical data solidified our choice in propeller design.

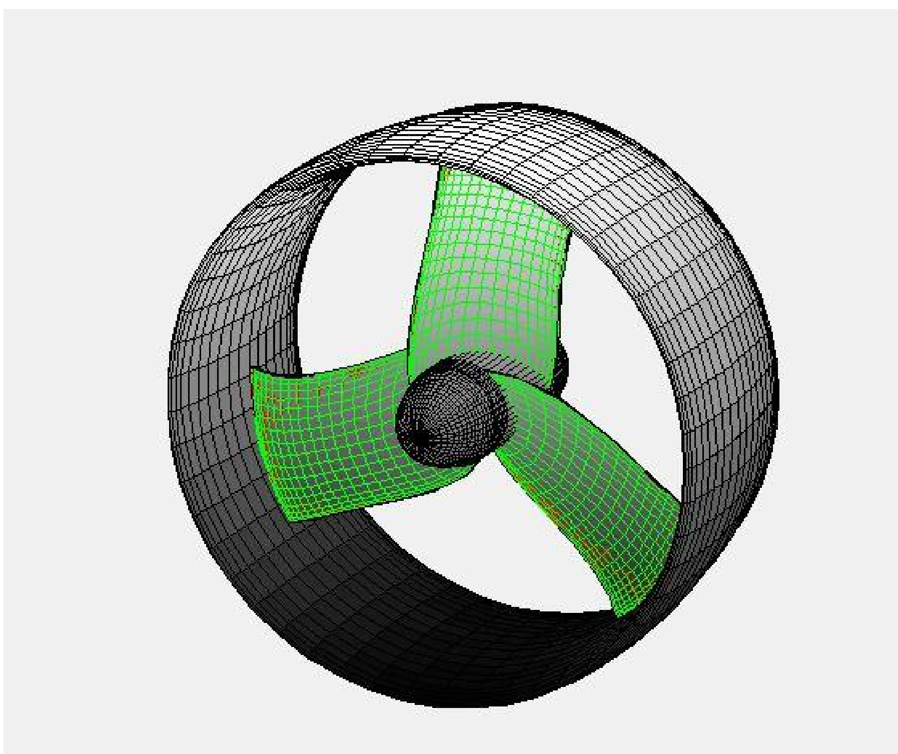


Figure 5 3D propeller geometry generated by OpenProp 3.3.4

Trolling Motor Research

For our application we require a low cost thruster which provides 105 lbf of thrust to propel the existing system. We've researched existing systems which include a motor and propeller system that could be modified for our parameters. Minn Kota manufactures a trolling motor which outputs 112 lbf of thrust from a 36V power supply, which can be seen in Figure 5. These trolling motors cost $850 for the entire system which includes the motor and controller for variable speeds. The current system is rated for a maximum depth of 10 feet and a run time of 2 hours at maximum power. These trolling motors offer a viable solution given that the system encompasses an aluminum housing, DC electric motor, and propeller.

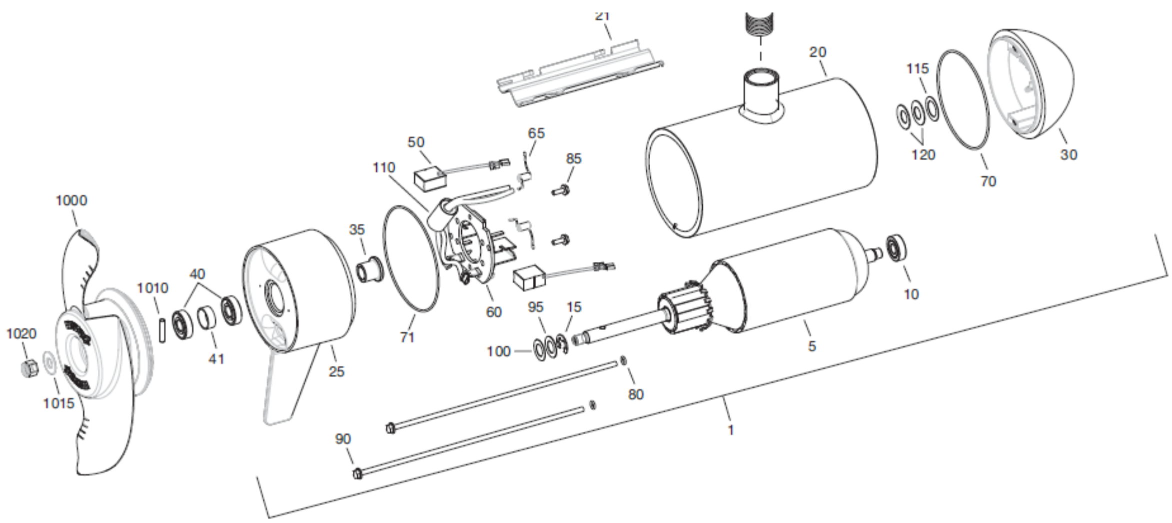


Figure 6 Minn Kota Riptide 112 lb trolling motor (exploded view) [9]

Several thrusters were found that have been hand built utilizing inexpensive material for individual needs. These projects are essentially do-it-yourself (DIY) garage build thrusters using simple components and low cost materials for a submersible propulsion system. The system typically includes a stock boat propeller and DC brushless motor which is enclosed within a plastic housing and sealed using O-rings and shaft seals. These projects are rated for minimal depth (<30 ft), however the use of inexpensive materials and simple designs are useful design considerations for our application.

Objectives

Low Cost

Designing and fabricating a thruster at a relatively low cost is one of the primary goals of this project, as it is the main dimension that distinguishes our product from its competitors in the market. The current system utilizes thrusters that cost about $17000 total, which represents a

significant cost for a disposable system. Our thruster is of significantly lower pricing given the material and motor we choose to pursue. Given our current trolling motor design we are estimating a final cost of under $3000. This price point would represent a cost savings of more than $11000 across the entire system.

Reliability

While we are trying to reduce cost, these thrusters are imperative for the overall system to work. It should also be seen that although a low-cost thruster with a short operational life is desired, the Navy still needs a product with a shelf-life of at least five years. Throughout this shelf life, the thrusters must stand up to transportation and harsh marine environments.

Performance

There is a requirement of 105 lb of thrust per thruster. In order to further reduce cost, efficiency becomes key. Increasing the efficiency of the thruster can potentially reduce the power draw from the system. The current thrusters have a peak combined power draw of 2.6 kW. Another major system requirement is the operational depth. Our model is based on a scalable depth, meaning that our design is rated for a particular depth, but can be easily modified to achieve greater depths.

Weight and Volume

The current vehicle has a wet weight of 255 lbs in descent. It is important that our new thruster has a weight that is comparable to the current design so as not to disturb the performance characteristics of the craft. It would also be ideal for the volume of our design to be similar to the current thrusters to make the bracketing transition as streamlined as possible. With this in mind, we would are aiming to keep weight and volume of our thruster within approximately 20% of the Tecnadyne 1060.

System Interface

In order to produce a plug and play system, the control system, power source, and bracketry all must be taken into consideration. The current control system that was reproduced is a +/- 5 volt analog input controller for speed control. The power source is a pos-neg DC direct from battery lead. The only requirement for bracketry is that the thrusters must be able to rotate 90 degrees. No-intermediate position is required.

Safety

While the vehicle itself will be remotely operated, service personnel will still be have to handle it before it is deployed. Some safety issues related to our thrusters involve ergonomic concerns due to weight, as well as the sound generated by the motors. Additionally, the thruster has a propeller and electrical components, which could present hazards to the operators. For marine applications in particular, it is important that electrical surfaces are insulated to prevent shocks to the operators. While it is impractical to eliminate all contact points from a moving propeller, a shroud is useful in reducing the risks associated with handling our thrusters.

Table 1 Design Specifications

Description	Target	Tolerance
Unit Price	$3000	Max
Shelf-Life	5 Years	Min
Control Interface	±5 V Analog	-
Minimum Storage Temperature	33°F	Max
Maximum Storage Temperature	145°F	Min
Operating Temperature (Water)	32-105°F	-
Operating Depth	2000 ft	Max
Pounds of Thrust	105 lbf	Min
Weight	11 lbs	±2.2 lbs
Volume (H x L x Dia)	587 in3	±117 in3
Peak Power Draw	2.6 kW	Max
Ability to Rotate on Vehicle	0°, 90°	Max

Noise Level	85 dB	Max
Propeller Access	Shroud built around side of propeller	Target
Electronics	All exposed electrical surfaces are potted	Target

As seen above, our objectives have been turned into design specifications. Most of these requirements lined up with engineering specifications one-to-one and were designated by SPAWAR. The main exceptions were noise and safety. Noise was cited as a minor concern during our meetings with SPAWAR, but a specific tolerable level was not specified. We deemed 85 dB in air (similar noise level to a snow blower) to be a reasonably quiet level as long as our thruster spends most of its time submerged. With regards to safety, we determined that the propeller should have a shroud to limit potential contact points, and any exposed electrical surfaces should be potted to protect the operators. These specific safety concerns are in addition to ergonomic (lifting) concerns related to weight and potential hearing damage from the noise level.

Further information on how we prioritized our engineering specifications can be found on our quality function diagram in Appendix B. The two principal customers we looked at when generating our QFD were the US Navy and the team responsible for manufacturing the thruster. ‘Low Cost’ was notably determined to be the most important customer requirement, since providing the US Navy with a low cost alternative to the current Tecnadyne 1060 thrusters is the basis of our project, and is also a top concern from a manufacturing standpoint. Reliability was also considered to be an important requirement as it was emphasized by our customer and ties in with more engineering specifications than any other requirement. Another requirement we concluded to be of significant importance was shelf storage and transportation. This category requires specific requirements including extreme weather conditions and exposure to saltwater spray over a period of several years. We considered the other customer requirements to be of roughly equal importance.

Design Development

While approaching the problem, we decided that testing early and often was key. One of our group members produced a first revision for this solution during a summer internship, which we used as a test model. We ran two parallel operations leading up to CDR: the first operation worked on a design of the second revision through theoretical calculations and analysis, while the second operation studied and analyzed the first revision in order to red flag possible critical points in the design that did not work in that model. In our test phase, we studied the thrust reported by the manufacturer compared to the actual measurable thrust and looked to identify root causes for performance deficiencies. We would have preferred to have our test results ready

to present for our preliminary design review (PDR), but that timeframe was pushed back due to scheduling issues. Our goal was to link these two operations and have a general design with critical points marked as soon as possible. With the team synched, a final design was to be generated and built. This would leave us enough time to run further tests on rev two and create a plan for a third revision if necessary.

Initial Testing

We selected the Cal Poly Pier in Avila Beach, CA as our testing site. The pier is owned by the university and is highly receptive to hosting student project, making it an ideal location. The prototype thruster developed over the summer utilized a modified Minn Kota Riptide Transom 112 trolling motor, advertised to deliver 112 lbf of thrust. Subsequent tests by SPAWAR showed that the prototype produced about half of that amount, making it well short of the 105 lbf requirement specified by the US Navy. We speculated that these losses could be attributed to a number of causes, including inadequate testing fixtures, the oil used in the housing, quality issues during manufacturing, and inaccurate thrust estimates by Minn Kota. Our objective for this initial round of testing was to determine the capabilities of the prototype and discover root causes for the poor performance observed in earlier tests. We aimed to achieve this by testing the prototype in different configurations and comparing performance to a stock trolling motor.

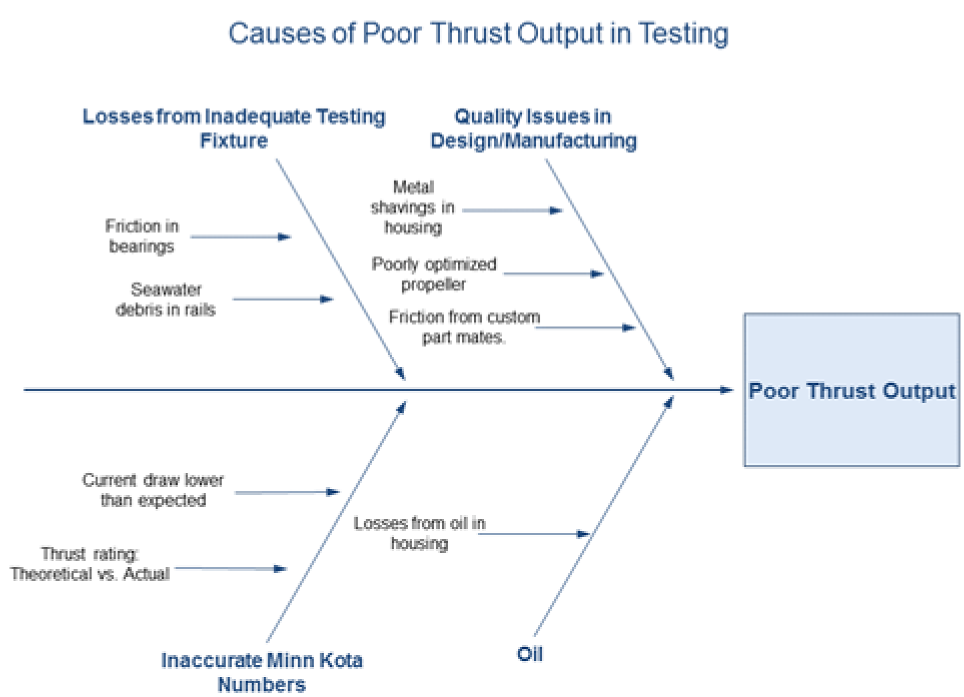


Figure 7 Possible root causes of the poor thrust output that we have identified.

We disassembled the prototype thruster on 25 October 2014 to look for possible causes of the low thrust output. Part of this process included draining the oil out of the thruster. We elected to reconstruct the thruster without the oil, in part because one of our testing modes was to run the prototype thruster without oil, and also because the original oil had turned black from metal shavings and grease. We also observed the testing fixture used by SPAWAR over the summer and noticed that some of the bearings had seized up due to seawater. Following the disassembly phase, we identified possible root causes for the poor thrust output, which are identified in Figure 7. The testing procedure was designed to identify which of these causes were most detrimental to the performance so they could be mitigated in the design phase.

On 30 October 2014, our team made a trip to the Cal Poly Pier for a tour and safety briefing and turned in a completed 'Pier Use Application' form.

Our first order of business was to design the bracketry needed for our testing fixture. The bracketry interfaces with a beam that rests underneath the dock of the Cal Poly pier, our thruster (the test subject), and a load cell. The thruster exerts a force on the end of a 10 ft aluminum pipe, which then exerts a force on our load cell, telling us the thrust of each configuration. This design tests for Bollard thrust, which is the thrust metric used by Tecnadyne and desired by SPAWAR . In contrast, the thrust figures reported by trolling motor companies like Minn Kota are produced using theoretical relationships between torque and revolutions per minute. This design also aims to reduce internal losses compared to the fixture used by SPAWAR over the summer by removing the bearings, which were highly susceptible to corrosion from seawater. During setup and testing, our load sensor and components of our bracket were tied down to fixed elements of the pier to ensure the safety of our equipment and personnel. We sent our part order to SPAWAR on 26 October 2014, and finalized our design on 2 November 2014.

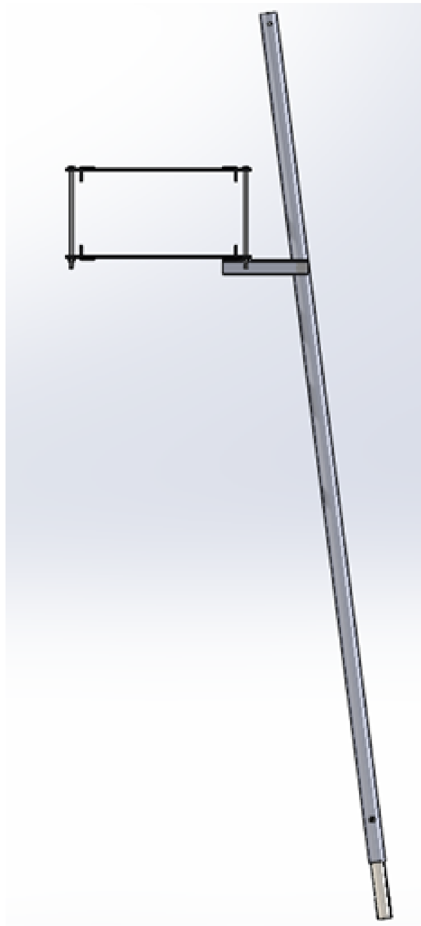


Figure 8 Testing Bracket

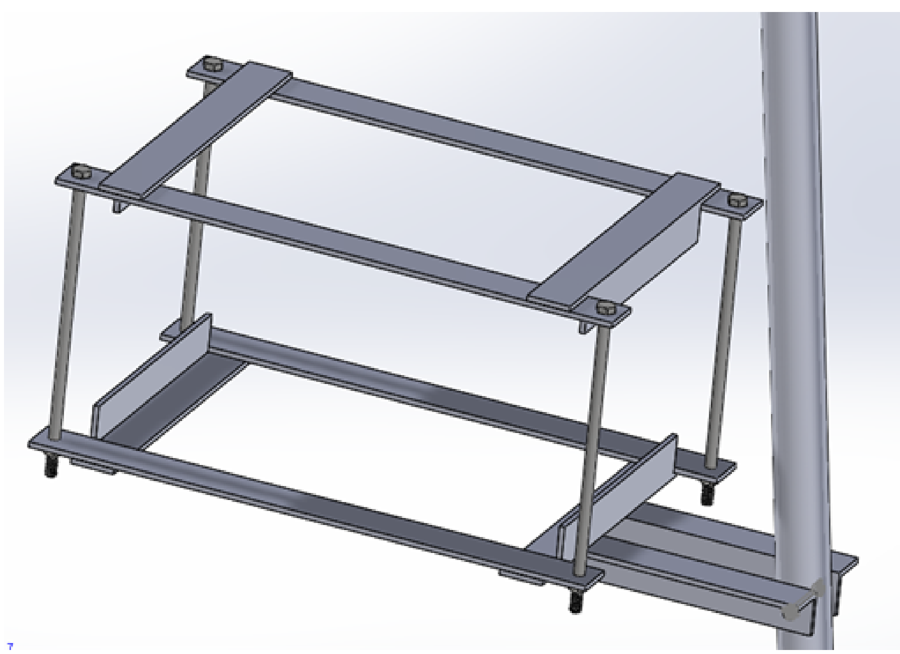


Figure 9 Close-up of bracketry that interfaces with beam.

Table 2 Test Matrix

Mode	Test of Thrust Output for Trolling Motor (lbf)																		
	Voltage Input (V):	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36
Modified Thruster, No Oil																			
Modififed Thruster, Oil-filled																			
Trolling Motor, Stock Configuration																			

Design Concepts

Our decision process has taken a slightly different route than the one outlined by the success guide because of the nature of our project. Danny Meritt has already spent time working with SPAWAR to design and fabricate an initial prototype. With the input from his work over the summer, we narrowed our concepts down to three distinct choices. Our first option was a continuation of Danny's previous work. He opted to develop a common off the shelf (COTS) trolling motor to interface with the Navy's vehicle. The trolling motor is the Minn Kota Riptide Transom 112. It provides a low cost platform which meets the required thrust criteria and only costs $850. By purchasing a trolling motor, we avoid the complicated task of designing or purchasing a propeller and pairing a motor with it. While this is an appealing option, a trolling motor propeller is not ideal for an ROV. Most thrusters designed specifically for an ROV use shrouded, three or four bladed propellers. While we can shroud the trolling motor prop, more blades at a fixed diameter increases blade area and therefore thrust. In our final design, propeller diameter is limited and tests carried out previously by Danny Meritt indicated that the thruster didn't meet advertised thrust numbers. While it was too early at that point to attribute the poor results to only the geometry of the stock propeller, we determined that it was likely a root cause.

Our second and third options were proprietary designs. The second thruster design is similar to current thrusters on the market. The thruster is powered by a brushed DC motor. Sealing a thruster to withstand the pressures at depths over 1000 feet is expensive. To eliminate the need for high quality shaft seals, a common industry practice is to backfill the entire thruster housing with mineral oil and install a pressure compensator. This keeps the differential pressure across the housing to a predetermined value and allows the thruster to operate at greater depths.

The third concept is similar to the second idea in that we plan to design the thruster entirely. It differs however in that this thruster will be open to the seawater. By using a DC brushless motor and potting all the electronics, the motor can run underwater without any seals. As with an oil filled motor, friction losses will be present when pushing the magnets through water. This design has been proven on a much smaller scale by BlueRobotics, who have recently started making thrusters open to sea water through a successful Kickstarter campaign.

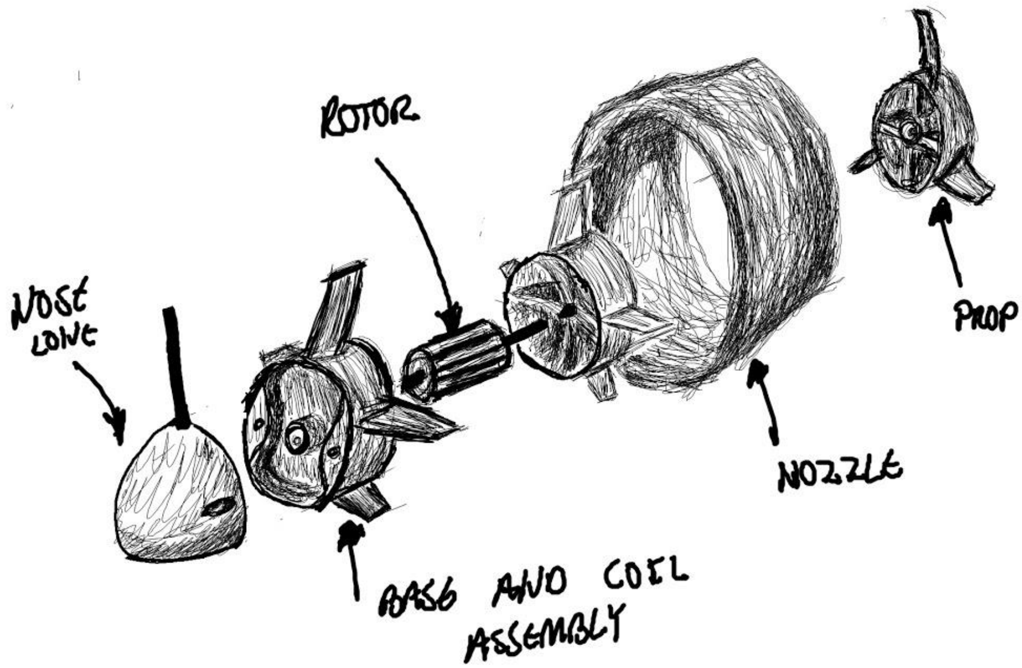


Figure 10 Sketch of design open to seawater.

Both the second and third concepts require self-built propellers. We have already spent some time exploring possible solutions to optimizing a propeller for our thruster using OpenProp. This tool has been extensively tested against experimental data and effectively models moderately loaded propellers. Additionally, it models the interaction between a propeller and a nozzle.

Initial Test

Internal delays with our part shipments forced us to delay our scheduled test day from the planned date of 3 December 2014. Our full part shipment arrived on 5 January 2015, but machine shop closures in the opening week of the quarter further delayed our fabrication date to 12 January 2015. Fabrication of our testing fixture was wrapped up on 15 January 2015, allowing us to conduct a preparatory test run on 16 January 2015. While we were unable to collect any data due to time constraints, we verified that our testing bracketry interfaced with the beam underneath the pier as designed and were subsequently granted a key by the pier staff so we could conduct tests on the weekends.

Scale Calibration

Testing on our prototype thruster ran from 24-25 January 2015. We began our tests by verifying the accuracy of our scale. We achieved this by mounting our scale to the edge of the pier (in air) and hanging free weights off the long end of the aluminum tube. Our scale was tied down to a fixed point on the pier and the short end of the aluminum tube to measure the force exerted by

the weights. After taking the moment arm into account, we found our scale's readings were accurate to theoretical values within ±2 lbs, which we deemed to be acceptable as this was also the resolution of our scale.

Figure 11 Picture of our calibration setup.

Thrust Testing

Our testing apparatus was attached to the pier by mounting the steel frame to a beam that rests underneath the pier. The aluminum tube was then attached to a hinge point at the end of the steel frame, forming a fulcrum. The thruster was bolted to the bottom end of the tube, and the top end of the tube was tied to our scale, which was anchored to the lower platform.

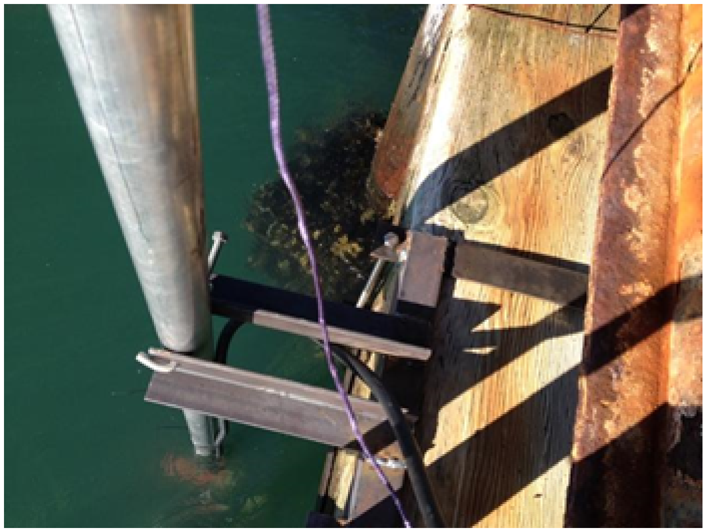


Figure 12 Steel frame mounted to beam.

Figure 13 Scale, tied to the aluminum tube and grating on the lower deck.

While our initial plan was to test both the prototype and stock trolling motor at multiple voltages, we instead elected to only collect data at peak voltage. This route still allowed us to evaluate the feasibility of a trolling motor solution, but saved us the trouble of testing at intermediate voltages. The oil-filled configuration was also omitted for this reason. Voltage was supplied to the thrusters through a set of three 12-V batteries connected in series. The results of our thrust tests are presented in Table 3.

Table 3 Thrust Test Results

Configuration	Recorded Thrust (lbf)	Adjusted Thrust (lbf)
Modified Trolling Motor (No Oil)	250	59.38
Stock Trolling Motor	290	68.88
Lever Arm Force Multiplier:		**4.2105**

Our test of the modified trolling motor yielded slightly higher numbers than those recorded by SPAWAR over the summer. SPAWAR's tests saw thrust numbers closer to 50 lbf, which suggests that our testing fixture was successful in eliminating some of the internal losses in SPAWAR's fixture. We also recorded a 16% improvement in performance for the stock Minn Kota trolling motor over the modified system, indicating that the modifications made to our prototype had a detrimental effect on performance. However, the stock trolling motor still saw performance 34.4% short of the 105 lbf requirement. For this reason, we decided that a trolling motor-based design was not a feasible solution to our problem and that further efforts should be shifted to our proprietary designs.

Final Design Summary

Our final design consists of six major components which make up the thruster system. The system includes a motor, center piece, nose cap, end cap, prop, and shroud. For our final design we chose to open our housing to seawater in order to cool the DC brushless motor and be able to run at high torque. In addition we will be coating all of the necessary electronics in thermally conducting and electrically insulating epoxy. An exploded view of our overall assembly is presented in Figure 14, and a model of the completed assembly is in Figure 15. Each subsystem is described in detail below.

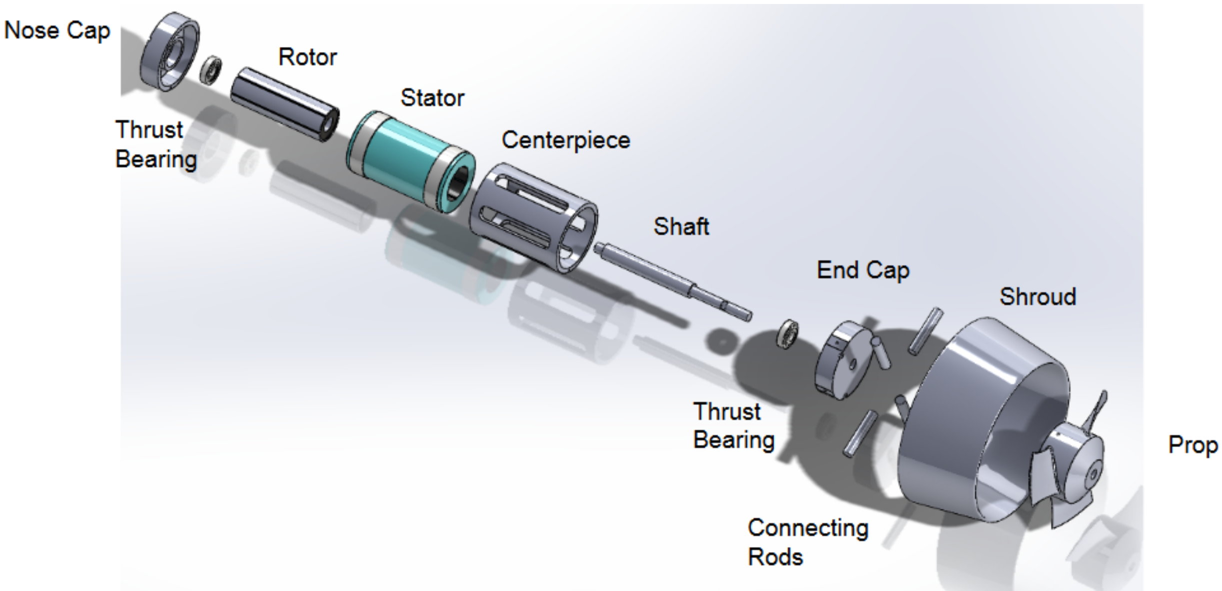


Figure 14 Exploded View of Thruster Assembly

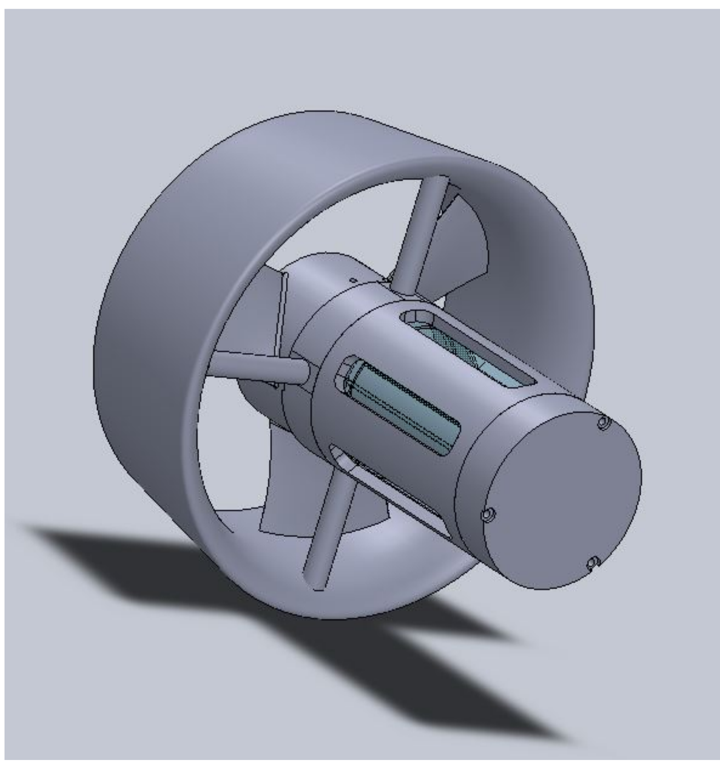


Figure 15 Model of the Final Assembly

Final Design: Motor

Description

The motor we chose for our design is an Allied Motion Technologies DC brushless motor model QB03405-X0X. This motor is rated for 8.6 ft-lbs of continuous torque, has a maximum RPM of 3,000, and has a stator stack with an outer diameter of 3.2 inches and a length of 4.5 inches. The entire motor specifications can be found in Appendix C. We chose this motor because we needed a relatively small brushless motor with high torque output and voltage requirements. The latter is important because the batteries on-board the current craft are rated for 150 V. The motor is equipped with a shaft that is keyed and mates with the prop using two set screws.

Final Design: Center Piece

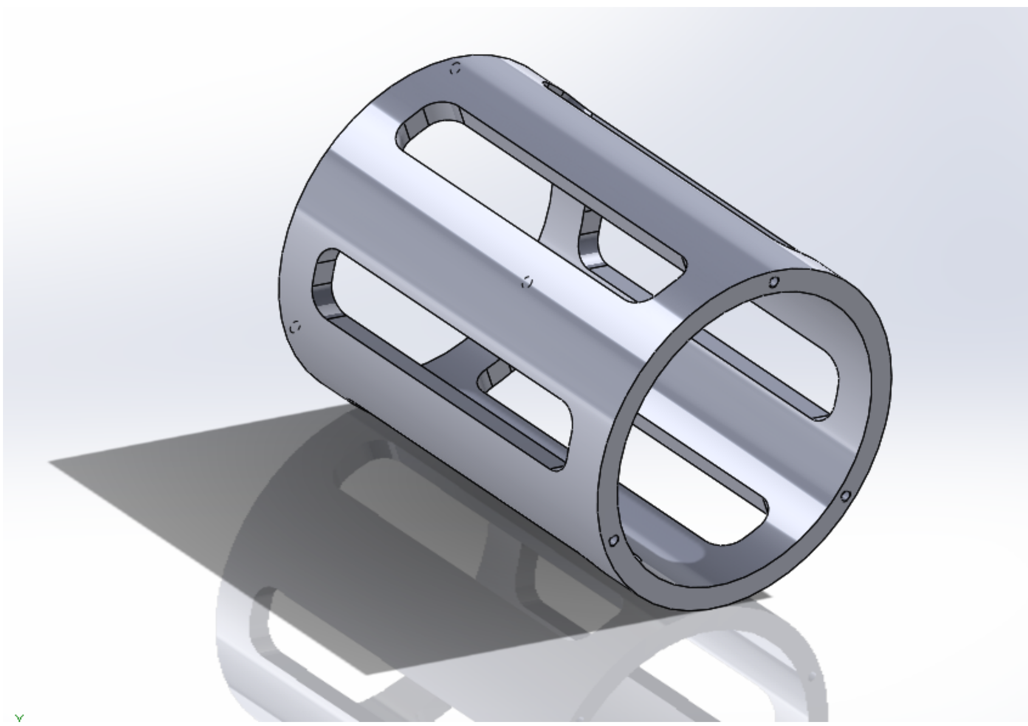


Figure 16 3D Model of center piece.

Description

For our center piece, we cut slots lengthwise to ensure proper fluid flow over the motor housing. The housing is equipped with three tapped holes on each end of the center piece to connect the end cap and nose cap. We used three set screws to hold the motor stator in place along with the epoxy coating.

Material Selection

We chose aluminum 6061-T6 for our center piece because of it is non-magnetic, lightweight, and easily machinable. In addition we do not have welding in any part of our design, so the metal will be able to retain its structural integrity. Aluminum is also relatively inexpensive which is crucial for our design requirements.

Structural Analysis

The driving factor for the thickness of our centerpiece was the connecting screws that had to tap into the cross sectional surface. The tapped screw holes can be seen in Figure 15 above. It was determined through a bolt analysis that ⅛" screws would give us a factor of safety of 5. This factor of safety is based off the driving factor for the screw which is the female threads in the centerpiece. The centerpiece is made of aluminum so if thread failure were to occur, it would be on the female threads instead of the steel threads of the bolt. These calculations can be found in Appendix F. With ⅛" screws, the centerpiece was set to ¼" thick. This thickness gives us a factor of safety of over 500 when calculating tensile stress through the centerpiece.

Final Design: Nose Cap/End Cap

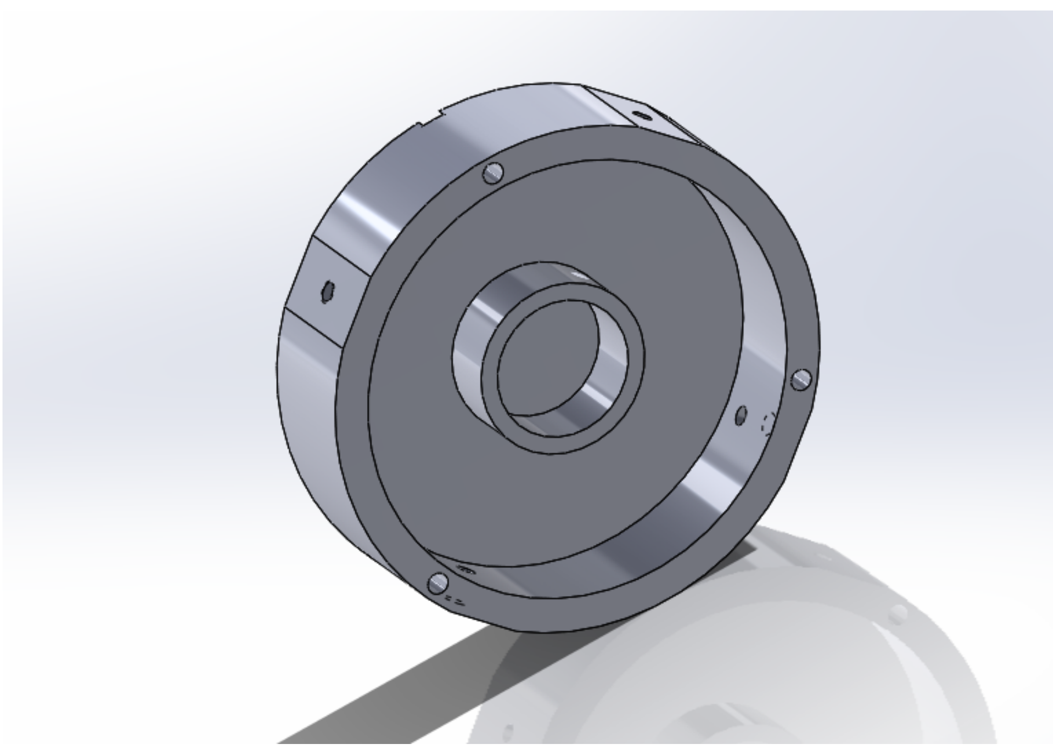


Figure 17 3D Model of end cap.

Description

The end cap and nose cap are designed with similar features including a seat to house the shaft bearing. The end cap is equipped with four flats to support the struts to mount the shroud. Both the end cap and nose cap have three holes drilled through the rim to be able to mount into the center piece.

Material Selection

We chose aluminum 6061-T6 for our nose and end cap because of its light weight and machinability. In addition we do not have welding in any part of our design, so the metal will be able to retain its structural integrity. Aluminum is also relatively cheap which is crucial for our design requirements.

Structural Analysis

The main thing to consider in the nose cap was the beam analysis of the three supports holding the seat for the thrust bearing. Deciding on a minimum cross sectional area of .25” by .4” gives us a factor of safety of 8. This also gives a suitable stiffness, and deflection to follow. Hand calculations can be found in the Appendix F.

Final Design: Propeller

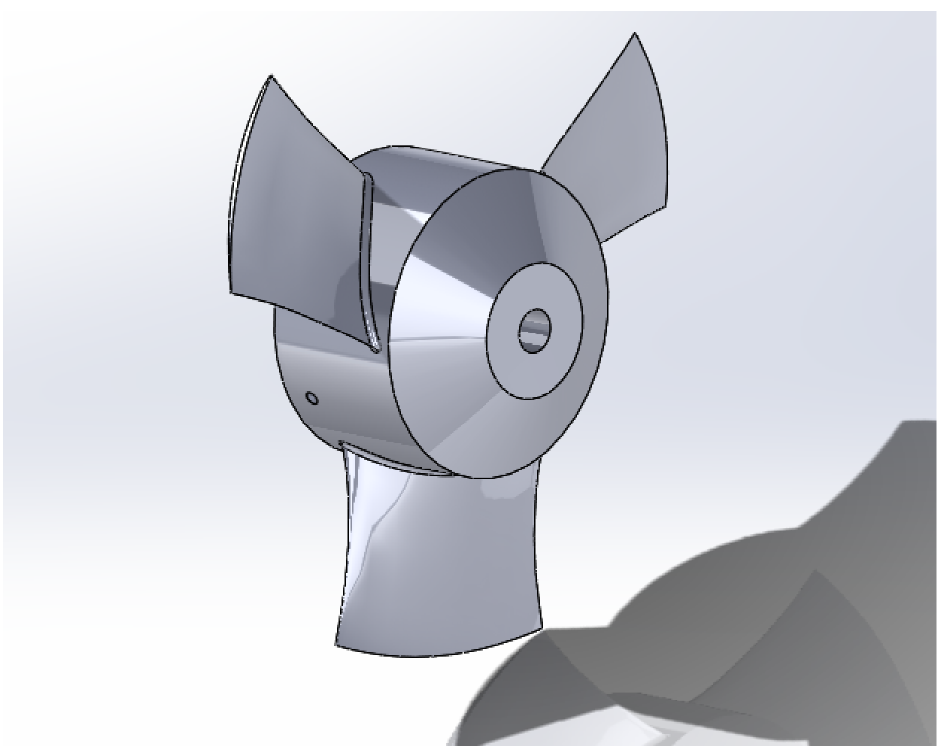


Figure 18 3D model of prop generated using Openprop V3.3.4.

Description

ROV propellers must provide thrust in multiple environments. Though most ROV's travel at speeds less than 1 knot, they must be able to maintain thrust while traveling in currents which poses a difficult problem due to the fact that propellers only operate effectively near their design conditions. When optimizing an ROV propeller, one must balance between performance near static conditions as well as good performance in currents. While the initial design conditions were centered on performance at vehicle speeds of less than one knot, the design evolved to be optimized at a vehicle speed of 2 knots in order for the system to be effective at both conditions. Propeller diameter was driven by the size of the thruster. The current Tecnadyne system uses a 7.5 inch propeller. Our system utilizes a 7.8 inch three bladed propeller optimized at 2500 rpm. Speed and torque decisions were mainly driven by cavitation and motor torque. Most DC brushless motors on the market producing the power needed for this system do not have the required torque. However high speed propellers are more prone to cavitation and are less efficient than slower spinning, larger propellers. These speed and torque settings provided a good balance between speed and torque and allowed for a reasonably sized motor. As previously stated, propeller design was done using OpenProp. We reached out for advice to Chris Rauch, CEO of Rauch engineering in Los Osos, CA. Chris is an expert in naval systems design and has years of experience with ROV design. He assured us that OpenProp's optimization is trustworthy. Lastly, to ensure sufficient blade thickness, the final propeller blades were matched to the suggested thickness to length ratio of a shrouded propeller in Principles of Naval Architecture Volume II - Resistance, Propulsion, and Vibration. See Appendix I for table [10].

Manufacturing

Initially, we tried to purchase a propeller from an existing ROV company but all companies were unwilling to share their propellers with us. Chris Rauch manufactures all of his propellers using a 3-axis mill using a ball nosed tool to finish the blades. We used the same approach to make ours. Material choice is again Aluminum 6061-T6 because of its low cost and its manufacturability. Current tool time for both sides is down to slightly under five hours on a Haas VF2.

Final Design: Shroud

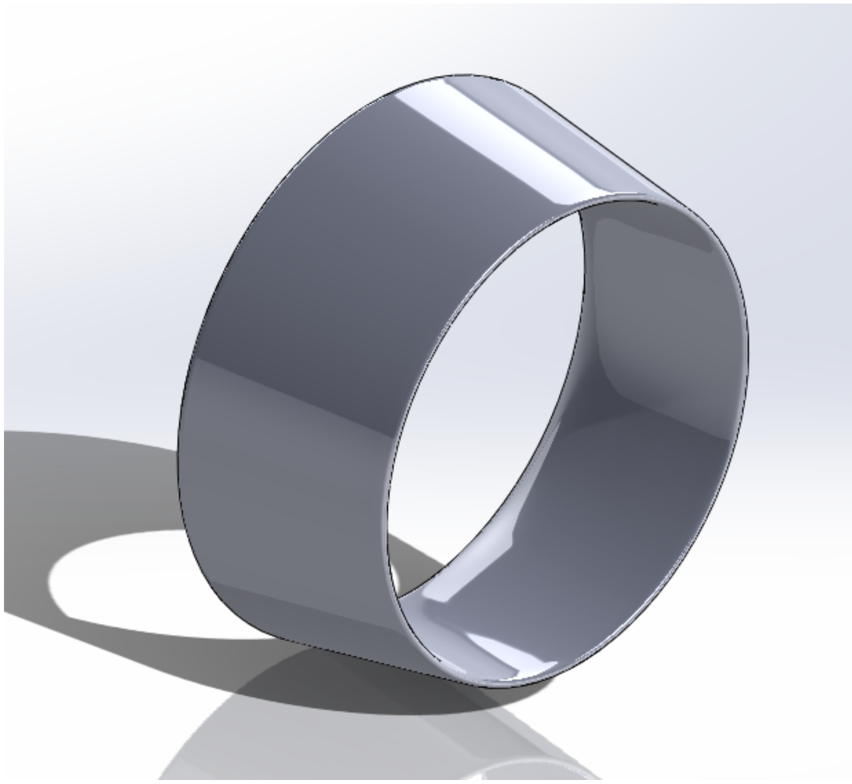


Figure 19 3D model of the shroud.

Analysis

In heavily loaded applications as previously mentioned, an accelerating nozzle is required. For a one directional thruster, the authors of Principles of Naval Architecture recommend a Kort 19a nozzle. See Appendix I for geometry.

Manufacturing

We originally planned to manufacture our shroud with selective laser sintering. The original shroud had struts built into the outer ring. We decided not to take this approach because our quote from Stratasys Direct Manufacturing was $626, which we deemed to be unacceptable for our budget requirements. We were also concerned with the structural integrity of the struts at the mating surfaces between the struts and the outer ring. We instead opted to remove the internal geometry and print the outer ring in ABS with through holes built-in. The shroud was coated in epoxy to mitigate porosity problems. The struts were ordered directly from McMaster-Carr and mount the shroud directly to the rear end cap. This solution will save us about $176 compared to the laser sintered shroud, and made our shroud less susceptible to failure.

Safety

Our two primary safety concerns are hazards associated with the propeller and the electronics. These hazards are also highlighted in the 'Senior Project Concept Design Hazard Identification Checklist' in Appendix E.

Propeller

The propeller will have sharp edges and rotate as fast as 3,000 rpm. This presents a potential safety hazard, but propeller operation is also critical to the performance of the thruster. In addition to the performance benefits of a shrouded propeller, the shroud will also serve to shield the operator from contact points on the leading edge of the propeller. The front of the propeller is still partially exposed, presenting a safety risk. However, this problem can be easily avoided by training operators to handle the thruster safely. Additionally, the thruster should only be operated in water, at which point the operators will be safe from the blades.

Electronics

It is especially important in marine applications to ensure that all electronics are properly insulated to protect operators from electric shock. Our electronics are coated in a thermally transmitting, electrically isolated epoxy. The epoxy will safely insulate the electronics, protecting the operators from short circuits.

Cost Analysis

Table 4 Summary of Cost Analysis

Cost Analysis						
Part Description	McMaster- Carr #	Material Selection	Material Length	Material Cost	Fabrication Cost	Total Cost
DC Brushless Motor	-	-	-	$700.00	-	$700.00
Motor Controller	-	-	-	$500.00	-	$500.00
Center Housing	9056K51	Aluminum 6061 T6	6 in	$29.06	$70.01	$99.07
Front End Cap	1610T29	Aluminum 6061 T6	1 in	$11.14	$90.17	$101.31
Rear End Cap	1610T29	Aluminum 6061 T6	1 in	$11.14	$92.52	$103.16
Propeller	1610T66	Aluminum 6061 T6	3 in	$114.61	$200.14	$314.75
Shroud	-	-	-	$450.00	-	$450.00
Shroud Struts x4	8974K28	Aluminum 6061 T6	24 in	$24.36	-	$24.36
Misc. Nuts/Bolts	92620A403/ 92158A205	Stainless Steel	-	$23.00	-	$23.00
Epoxy Resin	7548A11	-	-	$37.32	-	$37.32
Total				**$1900.89**	**$452.84**	**$2352.97**

Table 4 summarizes our cost analysis for the new thruster. The DC brushless motor and motor controller were quoted by Allied Motion at $700 and $500 respectively. The cost of the shroud was tabulated based on the volume of the thruster and pricing rates were provided by Cal Poly's 3D printing service. The remaining material costs are stock components priced by McMaster-Carr.

Fabrication rates were estimated using DFM Concurrent Costing software. The software receives inputs for manufacturing rates and processes to generate cost estimates. Production volume, batch size, plant efficiency, overhead, changeovers, defectives, machining parameters, and specialized tooling and fixturing are taken into account to generate an estimate that is as reflective of actual fabrication costs as possible. The results of these analyses are presented in Appendix G. For the sake of our cost analysis, the 'setup', 'process', and 'rejects' costs were summed to find the fabrication costs presented in Table 4. The material costs were obtained separately from McMaster-Carr because DFM Concurrent Costing charges raw materials on a per pound basis, which was less accurate for our application.

DFM Concurrent Costing was also used to justify our manufacturing approach to our propeller. As seen in Appendix G, the cost of producing our propeller was estimated to be $603.56, compared to the $317.36 cost of CNC machining. This is mainly due to the $16,458 tooling investment split over just 40 units, which lines up with our expectations.

Factoring in the quoted costs of the items being made by third-party suppliers, raw materials are expected to cost $1900.89 per thruster. Settling on accurate fabrication costs was more subjective. Our team at Cal Poly fabricated most of our parts, including the propeller, on CNC machines in an offsite shop with permission during downtime. Consequently, we did not need to pay for the machining costs on our prototype, but fabrication costs for SPAWAR in a full-production run are still critical to our design objectives. The DFM Concurrent Costing estimates are designed to be reflective of a full production run (40 units), and were estimated to be $452.84 across the system. Assembly costs were omitted in this instance because these costs will be charged internally to SPAWAR. This sums to a total system cost of $2352.97, which is $647.03 under our $3000 price point.

Design Verification Plan

Table 5 Low Cost Thruster Design Verification Plan/Report

Low Cost Thruster Design Verification Plan													
Report Date: 3-Mar-2015		Sponsor: SPAWAR Systems Center Pacific						Component/Assembly: Thruster			REPORTING ENGINEER: JUSTIN JANG		
TEST PLAN										TEST REPORT			
Item No	Specification or Clause Reference	Test Description	Acceptance Criteria	Test Respons	Test Stage	SAMPLES		TIMING		TEST RESULTS			NOTES
						Quantity	Type	Start date	Finish date	Test Result	Quantity Pass	Quantity Fail	
1	Shelf Life	Component Inspection/Product Life Rating	5 years	DW	DV	1	C	15-Jan-15	30-Jan-15				
2	Control Interface	Inspection	±5V Analog	PK	DV	1	D	15-Jan-15	30-Jan-15				
3	Storage Temp.	Analyze in extreme/controlled conditions	33-145 F	DM	DV	1	B	15-Jan-15	18-May-15				
4	Operating Temp.	Utilize pier tanks for operation in controlled water temperatures	32-105 F	JJ	DV	1	B	15-Jan-15	18-May-15				
5	Corrosion	Component Evaluation for Corrosion Properties	Reliable after shelf life and run time	JJ	DV	2	B	15-Jan-15	30-Jan-15				
6	Operating Depth	Request the use of Spawar ROV at various depths	0-2000 ft	DW	DV	1	C	20-Mar-15	18-May-15				
7	Thrust Output	CP Pier test using bracketry	105 lbf	PK	DV	3	B	3-Dec-14	18-May-15				
8	Weight	Test on Scale	8-13 lbf	JJ	DV	3	B	13-Apr-15	13-Apr-15				
9	Volume	Water Displacement Test	470-700 in^3	DM	DV	2	B	13-Apr-15	13-Apr-15				
10	Power Draw	Measure Voltage/Current Input using multimeter	<2.6 kW	PK	DV	3	B	13-Apr-15	13-Apr-15				
11	Propeller Access	Inspection	Shrouded	DW	DV	1	B	15-Jan-15	13-Apr-15				
12	Electronics	Inspection	Insulated/ Potted	PK	DV	3	B	15-Jan-15	13-Apr-15				

Table 5 shows an overview of proposed design verification tests for our thruster. Since our design was deemed to be novel and promising, our sponsor informed us after our critical design review that we would not need to strictly meet all of the specific criteria outlined earlier in the year. We were told that the goal of this project was to make a working prototype that can produce the required thrust at a significantly lower cost than competing thrusters. For this reason, our principal procedural test focused on obtaining thrust numbers. Theoretical qualifications for shelf life, storage temperature, operating temperature, control interface, corrosion, and operating depth will be sufficient for our purposes.

Thrust Test

Our first test validated the functionality of our testing fixture, and we intended on using this fixture as a basis for the tests on our finished prototype. The increased voltage requirements and complexity of our new design compared to the modified trolling motor necessitated some additional equipment and safety precautions.

The objective of these tests was to find the thrust output of our new design using the bollard pull method from our previous test on the trolling motor. SPAWAR wanted us to collect data points so we could find peak thrust and obtain relationships for thrust vs. RPM and thrust vs. power. They also wanted us to conduct an hour-long functional burn-in test at 80 lbf of thrust to verify the integrity of our motor. Our fixture was mounted to the pier during the previous test, and was left in place to eliminate the setup times in future tests.

During our first pier test, we noticed that the force exerted by the trolling motor deflected the aluminum pipe in our fixture by about 8 inches. Before our next test, we shortened the pipe by about a foot to mitigate this problem.

In addition we used an AC to DC power supply to run our drive which was used to control our thruster. We moved away from the three marine batteries used in our last test to ensure we reach peak power as well as granting us various operational points for data collection.

Management Plan

The following summarizes each team member's role within the group project. Throughout the project tasks were assigned accordingly. A detailed project timeline is displayed in a Gantt chart which can be found in Appendix A.

Table 6 Project Roles

Project Role	Lead	Description
Communications Officer	Danny Meritt	-Main POC with SPAWAR -Facilitates meetings/teleconference
Team Treasurer	Justin Jang	-Maintains team travel budget -Organizes team material budget
Recorder	Pascal Karam	-Maintain information repository for team (team binder, Google Docs, etc.)
Logistics Officer	David Whiteside	-Handles team logistics (scheduling, travel, reservations, testing facilities)

Manufacturing

The bulk of our manufacturing was done off-campus in a machine shop in Santa Barbara, CA. The tight dimensional tolerances required on our parts, as well as the complex geometry of our propeller were impossible to achieve with the manual machines in the Cal Poly machine shops. The shop in Santa Barbara gave us access to a 3-axis CNC mill, and since we did our machining on weekends, we were able to spend more time honing the processes and running long cycle times than we would on campus.

Propeller

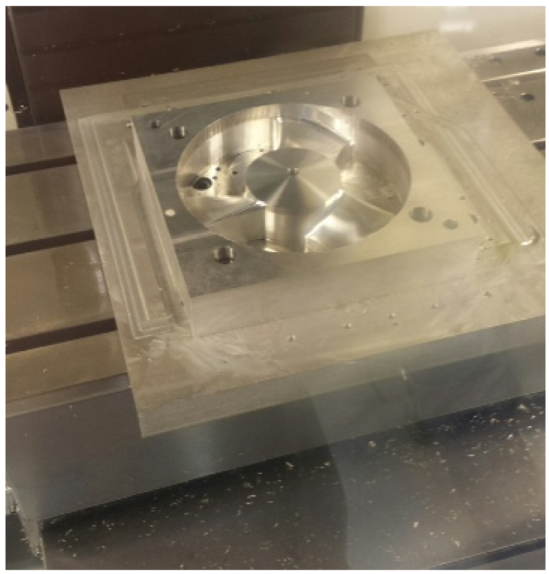


Figure 20 Machining the propeller.

The propeller was machined on a Haas VF2. OpenProp exported text file with the spline geometries to generate the propeller in Solidworks. The G-code was generated in CAMworks, a Solidworks plugin.

In order to hold the same machine zero for both sides of the piece, the propeller was cut out of 10" x 10" x 4" aluminum block with four counter bored holes and two reamed indicating holes drilled into the block prior to the propeller work. This allowed the block to be flipped while keeping the centerline of the piece in the same location. A custom fixture was machined for the indicating pins and 1/2" mounting screws.

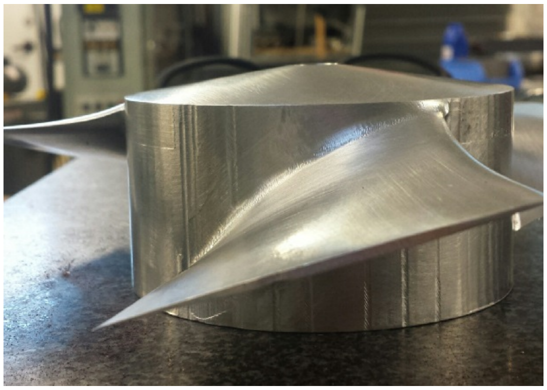


Figure 21 Finished propeller (First Revision).

Center Housing

Figure 22 Turning down the center housing.

The center housing was machined from an aluminum tube. The inner diameter was turned down on a manual lathe, and the slots were cut on a CNC mill.

End Caps

The end caps were machined from solid aluminum rod. The internal diameter was turned down on a manual lathe. The holes for the bearings, the four flat surfaces on the perimeter of the end caps, and the tapped holes were done a mill. The bearings were pressed into the end caps with an arbor press. Additional through holes for water flow were done on a drill press at Cal Poly.

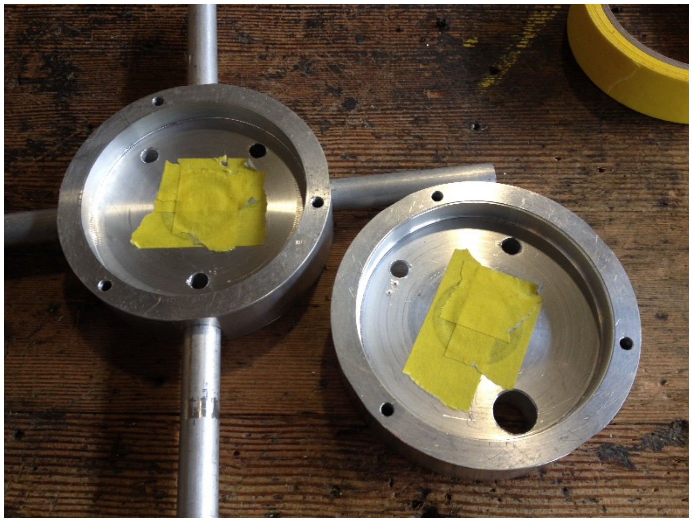


Figure 23 Finished end caps.

Shroud

The shroud was 3D printed in ABS plastic with an FDM machine at SPAWAR in San Diego.

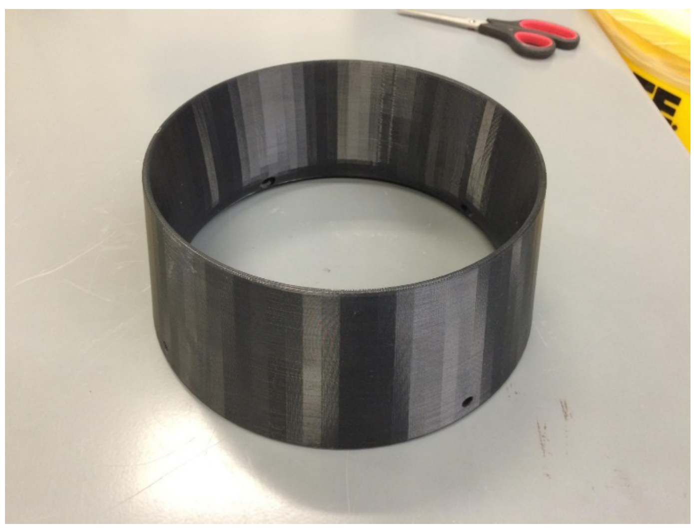


Figure 24 Printed shroud.

For ease of assembly, additional relief was added to each hole with a die grinder. An epoxy sealant was sprayed onto the shroud to mitigate porosity issues from the ABS printing process.

Struts

Figure 25 Struts with tapped holes.

The struts were cut from an aluminum rod using a band saw. The holes were drilled using a manual lathe and tapped by hand.

Shaft

The shaft was turned out of 1/2" steel shaft stock. The two 10mm ends were turned down and matched to the housing on a manual tooling lathe.

Differences from Proposed Design

The dimensions at the interfaces between the shaft and the bearing were matched rather than done strictly by our drawings since tolerance stacking made the fits difficult to hold.

Assembly

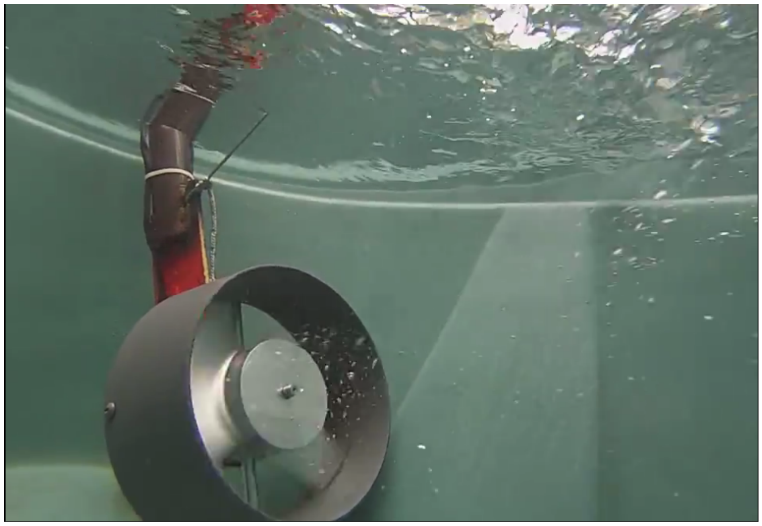


Figure 26 Finished Thruster in Water.

Potting

In order to ensure our electronics would not short in our motor, we decided to coat them with electrically insulating thermally conducting epoxy. For this process we taped off all of the stator magnets as well as the any other areas where the rotor will contact the stator. We poured in epoxy to completely submerge the solder joints as well as the motor circuit board.

Thruster

The first step in assembling was to glue the rotor magnets onto the shaft. For this process we used Loctite 680 shaft seal. The tolerance for the axial positioning of the magnets on the shaft was fairly tight and can be found in the assembly instructions for the motor, Appendix D. In order to ensure this tolerance was held, a custom assembly fixture was made. The same bonding agent was used for gluing the stator into the housing. The stator assembly comes with a reference edge on the mating surface for alignment purposes. The housing had a mating lip machined to align the reference edge of the stator assembly. The drawings for this are presented in Appendix H. Next the rotor was inserted into the housing. Caution was exercised to not chip the rotor magnets during assembly. The end caps were inserted over the shaft ends and positioned so that the rotor was balanced and concentric. This alignment was done by hand and proved more difficult than expected. A suggested improvement is outlined in the conclusion. Next, the prop was installed with the set screw on the flat shown in the drawing in Appendix H. Finally, the shroud was inserted over the propeller and onto the struts that are threaded onto the rear end cap. The shroud is fixed with screws into these struts.

Motor Drive Calibration

The motor drive required minor calibration to interface correctly with our motor. Most importantly, the current limit needed to be set at 20 Amps to prevent overheating. Additionally,

the zero offset for the input signal and the loop gain for the input signal were set to provide a maximum rotational velocity of 2700 RPM.

Figure 27 Motor drive from Advanced Motion Controls.

Pier Test

On 17 May 2015, we conducted a test on our completed prototype at the Cal Poly Pier in Avila Beach. Our two principal stakeholders from SPAWAR, Bret Thompson and Steve Whiteside, attended the test in-person to observe the performance of our thruster.

Seawater Test

Figure 28 Problematic seawater test.

Our initial plan was to use the fixture from the previous test. Our power supply was placed in a padded case on the lower deck, with the power cable running up to an outlet on the upper deck. However, the GFCI breaker in the outlet was tripped every time we attempted to supply power to the thruster. We speculate that this is due to an incomplete potting of the electronics in our thruster, either with the epoxy sealant that we applied ourselves or the shellacking on the coils provided by Allied Motion.

Freshwater Test

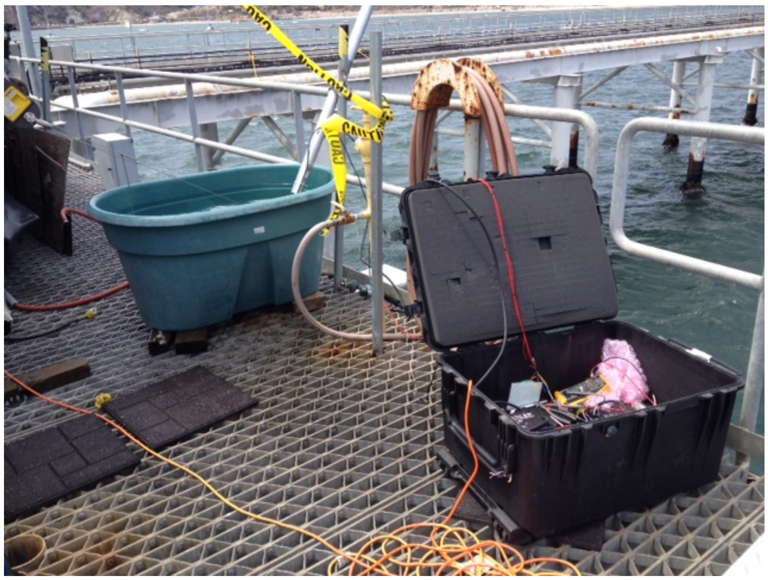


Figure 29 Improvised freshwater test with motor drive.

Since the grounding problem could be attributed to the ionization of the salt water, we decided to conduct an improvised test in a freshwater environment to obtain test results for our sponsors. We filled a tub on the upper deck of the pier with freshwater and secured the aluminum pole from our original fixture to the railing with band clamps. Our load sensor was tied between the lower end of the pole and a fixed point of the pier. With this setup, our thruster functioned as intended, but we suspect that there were losses in our measured thrust figures due to the band clamps and turbulence in the tub. We zip-tied a hose to the aluminum pole to keep the tub at a steady fill-level while the thruster was running.

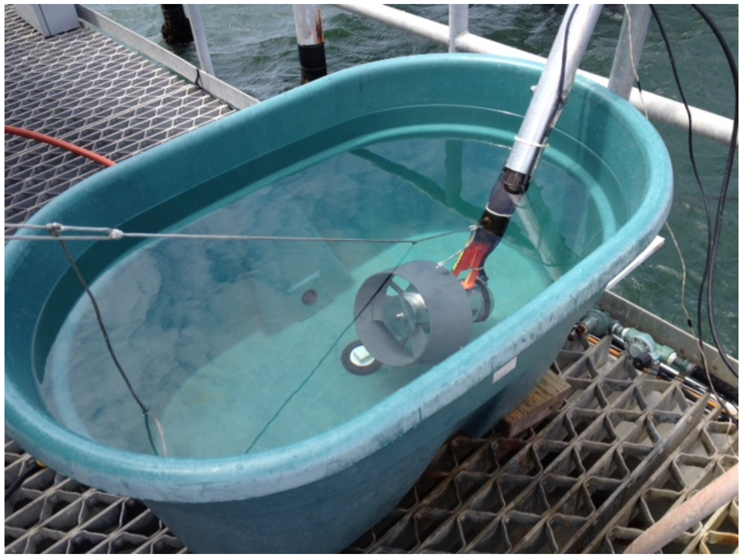


Figure 30 Thruster in tub.

Figure 31 Thruster at full power.

Final Results

From our fresh water test, we were able to obtain a steady interval of thrust based on RPM and Power outputted by the motor drive. Both the RPM and current where measured as a scaled voltage output from the motor drive. At maximum power we obtained a thrust of 95 lbf. This data can be seen in the figures below. One thing to note, is during our fresh water test the largest tank we had access to was approximately 300 gallons. This caused for a large amount of turbulence in the water. The propeller was audibly cavitating and even still, as seen below, the desired thrust was achieved. Under the conditions seen in the deployable environment of the

thruster, it can be assumed that the thruster would output more thrust. A numerical table with our test results is presented in Appendix L.

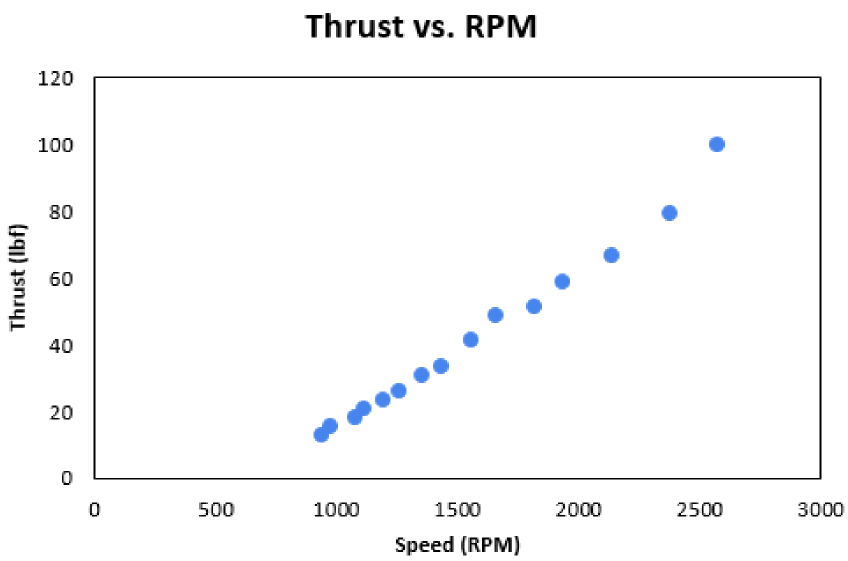


Figure 32 Thrust vs. RPM Results.

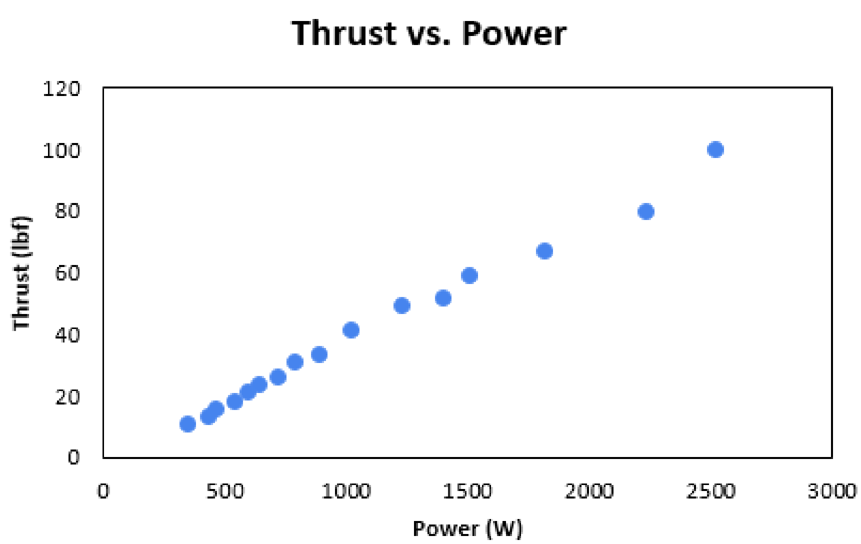


Figure 33 Thrust vs. Power Results.

For our final test, we operated the thruster at 80 lbf of thrust for one hour to satisfy our duration requirement. The thruster operated satisfactory with no sign of issues. Concluding the tests, we disassembled the entire thruster and inspected the components. We found no prominent defects or problems within the thruster. In addition there was minimal rust throughout the bearings and motor.

Conclusions and Recommendations

The final pier test yielded comparative results to what our team had strived for. We were able to obtain a maximum thrust of 100 lbf which was deemed a result of our motor drive not receiving the full input power from the pier outlet and cavitation cause by the small tank. The drive is rated for 20 A continuous current, though at peak thrust, we were only able to output 15 A.

For ease of assembly, an alignment lip should be added to the mating surface of the center housing and end caps. A slight taper should be added on these lips so that as the end caps are tightened together, the assembly centers itself. We found that when assembling the thruster, it was difficult to get the rotor concentric within the stator. This is due to the strong magnetic attachment pulling the rotor to one side. With this new addition, we would be able to tighten down the end caps and have the motor align itself.

Another thing to consider would be to increase the size of the flat on the shaft, to give the propeller's set screw more hold. Before we applied thread locker to the prop set screw, we noticed that the prop was beginning to slip on the shaft. Having a larger flat would ensure more holding strength between the prop and shaft.

The potting issues were also a concern. We initially believed that our epoxy coating was comprehensive, but an exposed electrical surface seems to be the reason why our thruster failed to operate in seawater when powered by an outlet. A major facet of SPAWAR’s continued development of this project will be to identify the root cause of our potting issues. Allied Motion will also be contacted to verify the integrity of the shellacking on their motor coils, which were not covered by our coating process. For future iterations, we have the option to purchase a motor stator with the wiring and circuit board already coated in epoxy among other specific alterations to meet our specifications. Another change we would implement would be to completely submerge the electronics within the epoxy, rather than trying to tape off the area and pump epoxy into the cavities. We would like to implement an electrical test prior to a full sea test, we can ensure that the motor was potted correctly.

The next issue we want to address was our uncertainty in propeller design. Being as we based on research on OpenProp, we would like to be able to test various blade geometries to ensure we are using the most efficient design. Tecnadyne thrusters are equipped with removable prop blades. The come in two parts, the hub which is fixed to the shaft and removable blades. This would allow us to easily test different prop geometries.

We would also like to make modifications to our center housing. In future revisions we would cut a slit on the through the housing and drill to bolts to be able to clamp down the housing onto the motor. In our current model we used loctite to hold our stator in place. This creates an issue if the motor fails, we would be required to remake the housing as well. This would also allow us to test various motors types assuming they have the same outer diameter.

Our revised production cost estimate came to $3400.50 per unit, which is slightly higher than our target, but still at the low-end of the $3000 to $5000 goal set by SPAWAR. The increase over our previous estimate of $2350.00 is mainly due to the addition of bearings and a more

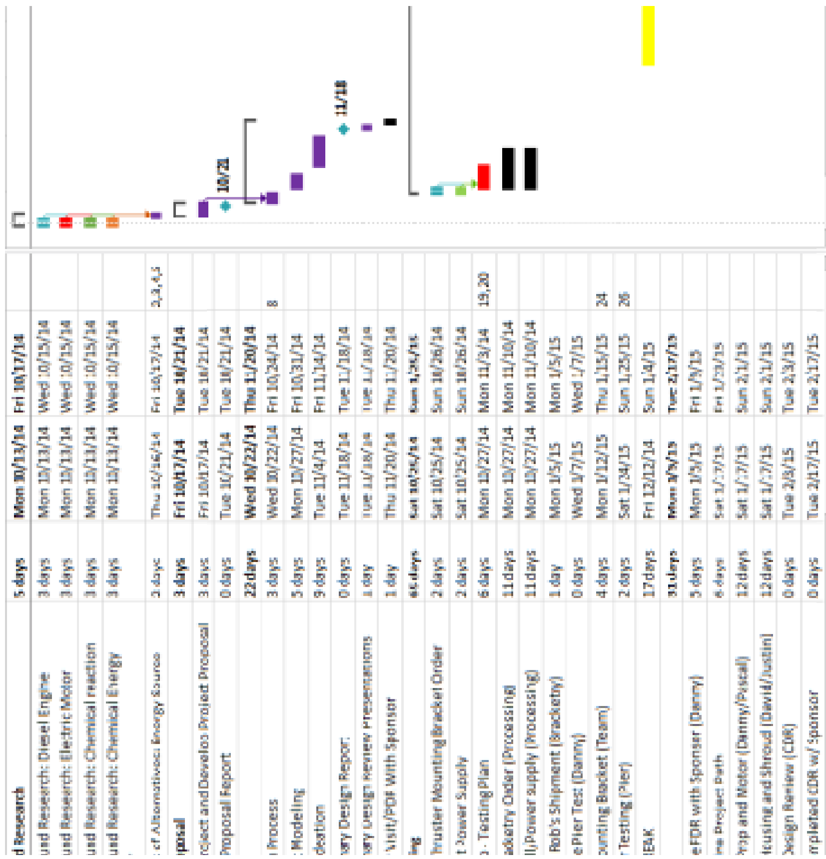
expensive than expected motor drive. The omission of bearings from the cost analysis was an oversight on our part, most likely since they were originally missing from our original assembly drawings in Appendix H. The bearings were always a feature of the design, but were a relative afterthought during the critical design phase because specific dimensions of the motor shaft were unknown at the time. Appendix H has since been updated with the bearings added in. The machine time on the propeller was also longer than anticipated. Our revised cost estimate assumes that all of the machine time is sourced to an external machine shop. SPAWAR would see this cost reduced by approximately $800 if they did all of their machining on-site. Our revised cost breakdown is presented in Appendix M.

Overall, we were pleased with the performance of our prototype, and look forward to seeing the project continued at SPAWAR this summer. Bret Thomson and Steve Whiteside were excellent mentors throughout this project, and SPAWAR's support was instrumental to our efforts. We would like to thank our advisor, John Fabijanic, for his guidance throughout the year. We would also like to acknowledge Advanced Motion Controls, who gave us a generous discount on our motor drive.

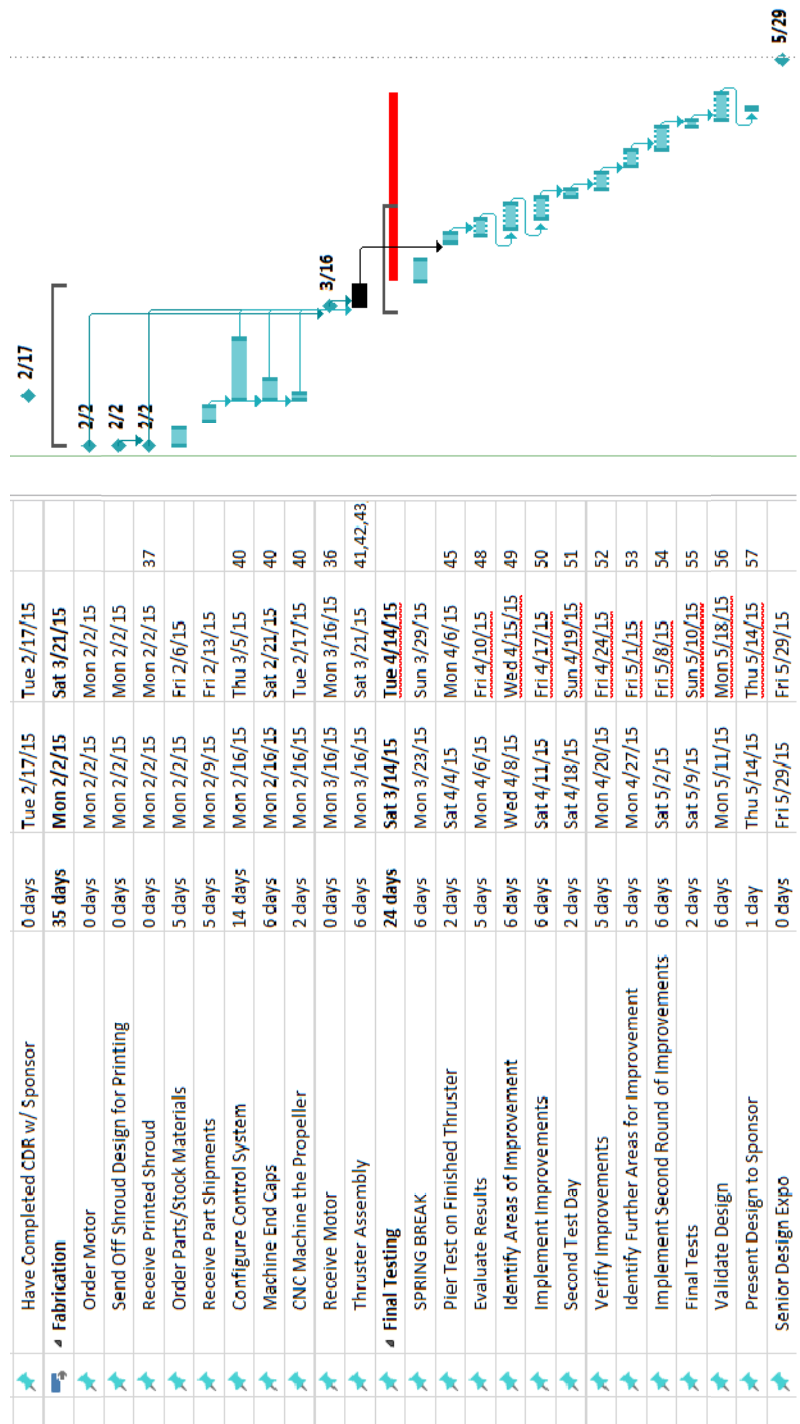
Appendix A

Gantt Chart

Table 7 Gantt Chart



d Research	5 days	Mon 10/13/14	Fri 10/17/14	
und Research: Diesel Engine	3 days	Mon 10/13/14	Wed 10/15/14	
und Research: Electric Motor	3 days	Mon 10/13/14	Wed 10/15/14	
und Research: Chemical reaction	3 days	Mon 10/13/14	Wed 10/15/14	
und Research: Chemical Energy	3 days	Mon 10/13/14	Wed 10/15/14	
: of Alternatives: Energy Source	2 days	Thu 10/16/14	Fri 10/17/14	2,3,4,5
oposal	3 days	Fri 10/17/14	Tue 10/21/14	
roject and Develop Project Proposal	3 days	Fri 10/17/14	Tue 10/21/14	
Proposal Report	0 days	Tue 10/21/14	Tue 10/21/14	
	22 days	Wed 10/22/14	Thu 11/20/14	
Process	3 days	Wed 10/22/14	Fri 10/24/14	8
: Modeling	5 days	Mon 10/27/14	Fri 10/31/14	
ideation	9 days	Tue 11/4/14	Fri 11/14/14	
nary Design Report	0 days	Tue 11/18/14	Tue 11/18/14	
nary Design Review Presentations	1 day	Tue 11/18/14	Tue 11/18/14	
Visit/PDF With Sponsor	1 day	Thu 11/20/14	Thu 11/20/14	
ing	65 days	Sat 10/25/14	Sun 1/25/15	
Thruster Mounting Bracket Order	2 days	Sat 10/25/14	Sun 10/26/14	
t Power Supply	2 days	Sat 10/25/14	Sun 10/26/14	
p - Testing Plan	6 days	Mon 10/27/14	Mon 11/3/14	19,20
acketry Order (Processing)	11 days	Mon 10/27/14	Mon 11/10/14	
ll/Power supply (Processing)	11 days	Mon 10/27/14	Mon 11/10/14	
Rob's Shipment (Bracketry)	1 day	Mon 1/5/15	Mon 1/5/15	
e Pier Test (Danny)	0 days	Wed 1/7/15	Wed 1/7/15	
ounting Bracket (Team)	4 days	Mon 1/12/15	Thu 1/15/15	24
r Testing (Pier)	2 days	Sat 1/24/15	Sun 1/25/15	26
EAK	17 days	Fri 12/12/14	Sun 1/4/15	
	31 days	Mon 1/5/15	Tue 2/17/15	
e FDR with Sponsor (Danny)	5 days	Mon 1/5/15	Fri 1/9/15	
ine Project Path	6 days	Sat 1/17/15	Fri 1/23/15	
Prop and Motor (Danny/Pascal)	12 days	Sat 1/17/15	Sun 2/1/15	
Housing and Shroud (David/Justin)	12 days	Sat 1/17/15	Sun 2/1/15	
Design Review (CDR)	0 days	Tue 2/3/15	Tue 2/3/15	
mpleted CDR w/ Sponsor	0 days	Tue 2/17/15	Tue 2/17/15	

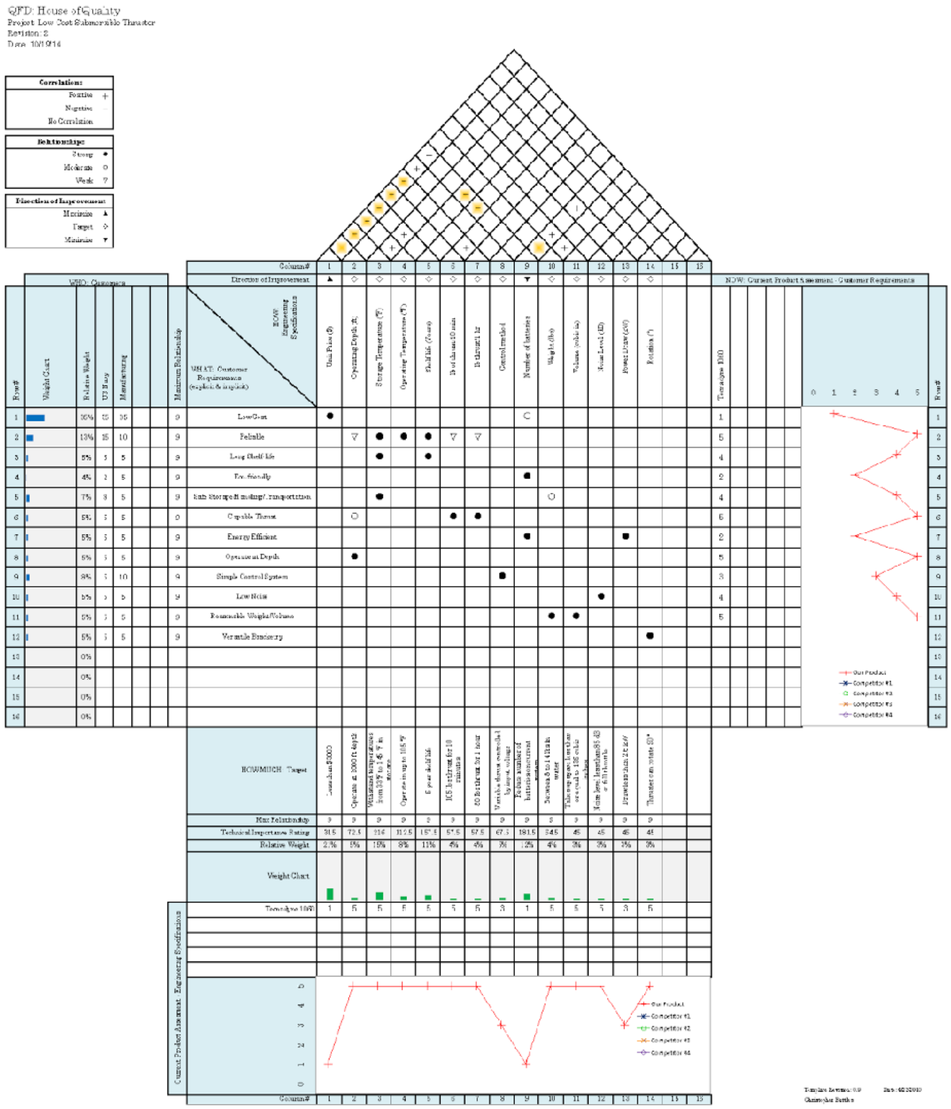


Task Name	Duration	Start	Finish	Predecessors
Have Completed CDR w/ Sponsor	0 days	Tue 2/17/15	Tue 2/17/15	
Fabrication	**35 days**	**Mon 2/2/15**	**Sat 3/21/15**	
Order Motor	0 days	Mon 2/2/15	Mon 2/2/15	
Send Off Shroud Design for Printing	0 days	Mon 2/2/15	Mon 2/2/15	
Receive Printed Shroud	0 days	Mon 2/2/15	Mon 2/2/15	37
Order Parts/Stock Materials	5 days	Mon 2/2/15	Fri 2/6/15	
Receive Part Shipments	5 days	Mon 2/9/15	Fri 2/13/15	
Configure Control System	14 days	Mon 2/16/15	Thu 3/5/15	40
Machine End Caps	6 days	Mon 2/16/15	Sat 2/21/15	40
CNC Machine the Propeller	2 days	Mon 2/16/15	Tue 2/17/15	40
Receive Motor	0 days	Mon 3/16/15	Mon 3/16/15	36
Thruster Assembly	6 days	Mon 3/16/15	Sat 3/21/15	41,42,43
Final Testing	**24 days**	**Sat 3/14/15**	**Tue 4/14/15**	
SPRING BREAK	6 days	Mon 3/23/15	Sun 3/29/15	
Pier Test on Finished Thruster	2 days	Sat 4/4/15	Mon 4/6/15	45
Evaluate Results	5 days	Mon 4/6/15	Fri 4/10/15	48
Identify Areas of Improvement	6 days	Wed 4/8/15	Wed 4/15/15	49
Implement Improvements	6 days	Sat 4/11/15	Fri 4/17/15	50
Second Test Day	2 days	Sat 4/18/15	Sun 4/19/15	51
Verify Improvements	5 days	Mon 4/20/15	Fri 4/24/15	52
Identify Further Areas for Improvement	5 days	Mon 4/27/15	Fri 5/1/15	53
Implement Second Round of Improvements	6 days	Sat 5/2/15	Fri 5/8/15	54
Final Tests	2 days	Sat 5/9/15	Sun 5/10/15	55
Validate Design	6 days	Mon 5/11/15	Mon 5/18/15	56
Present Design to Sponsor	1 day	Thu 5/14/15	Thu 5/14/15	57
Senior Design Expo	0 days	Fri 5/29/15	Fri 5/29/15	

Appendix B

QFD Diagram

Table 8 QFD Diagram



Appendix C

Allied Motor Spec. Sheet

Allied Motion Technologies: TULSA Jan-16-2015 Pg 1

QB03405-X0X OR-09158A CAL POLY

SIZE CONSTANTS **

Parameter	Symbol	Unit	Value
Maximum Rated Torque	Tr	ozin	3237.949
		Nm	22.865
Maximum Continuous Stall Torque	Tc	ozin	1642.318
@Temperature Rise 100.000°C		Nm	11.597
Motor Constant	Km	ozin/sqrt.w	78.200
		Nm/sqrt.w	0.552
Electrical Time Constant	Te	msec	3.978
Mechanical Time Constant	Tm	msec	0.958

Angular Acceleration (theoretical)		rad/sec²	72128.000
Thermal Resistance *	TPR	°C/watts	0.140
Maximum Cogging Torque	Tf	ozin	11.000
	Nm	0.078	
Viscous Damping	Fi	ozin/rpm	5.199E-3
(Infinite Source Impedance)		Nm/rpm	3.671E-5
Rotor Inertia Frameless	Jm	ozins²	0.045
	kg-m²	3.170E-4	
Motor Weight Frameless	Wt	oz	124.803
	kg	3.538	
No. of Poles	P	6	

* TPR Assumes motor mounted to aluminium heat sink

15.000 x 15.000 x 0.250 inches (Water cooling)

** @ Ambient Temperature, 20.0000

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Allied Motion Technologies: TULSA Jan-16-2015 Pg 2

QB03405-X0X OR-09158A CAL POLY

Winding Constants *

Parameter	Symbol	Unit	VALUE
Design Voltage	Vp	volt	150.000
Peak Torque, ±25%	Tp	ozin	3237.949
		Nm	22.865
Peak Current, ±15%	Ip	Amps	58.122
Torque Sensitivity ±10%	Kt	ozin/A	55.709
		Nm/A	0.393

No Load Speed	Snl	rpm	3355.601
		rad/sec	351.398
Voltage Constant ±10%	Kb	V/krpm	41.196
		V/rad/sec	0.393
Terminal Resistance ±12%	Rm	ohms	0.508
Terminal Inductance ±30%	Lm	mH	2.019

RMS TORQUE PERFORMANCE

Design Voltage	Vp	volt	150.000	
Continuous Power Output @	Power	watt	2618.985	
	Horsepower	3.512		
Temperature Rise: 72.084°C	Torque	ozin	1416.655	
COOLING :		Nm	10.004	
(Water cooling)	Speed	rpm	2500.000	
Ambient Temperature 20.000°C	IPhase	amperes	29.878	
	I(dc-link) amperes	20.892		
	Efficiency %	83.570		

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Allied Motion Technologies: TULSA Jan-16-2015 Pg 3

QB03405-X0X OR-09158A CAL POLY

UNHOUSED MECHANICAL

Stator Stack OD	3.200 inch	81.280 mm
Stator Stack Length (Machined)	4.500 inch	114.300 mm
Stator ID	1.830 inch	46.482 mm
Number of Phases	3	
Phase Connection	DELTA	

Length Over Coil (Maximum)	5.424 inch	137.770 mm
End Turns OD (Maximum)	2.950 inch	74.930 mm
End Turns ID (Minimum)	1.880 inch	47.752 mm
Lead Wire Gage	14.0 AWG	
Lead Wire Length	12.000 inch	304.800 mm

Rotor OD	1.770 inch	44.958 mm
Rotor ID	0.500 inch	12.700 mm
Rotor Axial Length "B"	5.000 inch	127.000 mm

Number of Poles 6

Appendix D

Allied Technology Motor Assembly Instructions

Allied Motion
EMOTEQ

Emoteq Corporation
10002-B East 43rd St. South
Tulsa, Oklahoma 74146
Tel: (918) 627-1845
Fax: (918) 660-0207
www.emoteq.com

Rotor hub assembly procedure.
QB Frameless Motor Series

Rotor hub assemblies for frameless motors are supplied as sets. The number of sets supplied for any particular motor will depend on the stack height of the stator assembly. Chart 1 lists the number of sets for each motor series. Each motor will have a rotor set which consists of two magnet assemblies, one for the hall sensors and one for the stator core. (See Fig. 1) Additional rotor sets if required consists of magnets bonded to a hub. Each hub is designed with locators to ensure correct magnet pole alignment. North pole magnets are positioned over each locator.

Caution must be observed when handling, transporting or storing rotor assemblies. Strong magnetic forces are present which can cause the sets to impact one another or a foreign metal object. Such impacts will cause damage to the magnets. Sets must be protected from possible damage until assembly is required.

For frameless motors, the customer is accepting responsibility for the design of the shafts, housings, endbells and/or other supporting elements of the motor. Each customer will have his own unique design, so it is impossible to cover every assembly method for the rotor sets. The procedure described below is used by Emoteq to assemble rotor sets to motor shafts and should be used as a guide for your assembly procedure. Please contact Emoteq for assistance on rotor assemblies that cannot be covered by this procedure.

Assembly: Refer to Fig. 2-6

1. Clean shaft, rotor hub ID and hub face with alcohol or acetone.
2. Support shaft vertically in arbor press. Use support block as a height gage to position rotor sets from end of shaft.
3. Apply Loctite 680 to serrated area on shaft.
4. Slide first rotor set onto shaft until it is in contact with serrations. Locator ridges must face up.
5. Place a nonmagnetic collar on the hub face and press rotor set onto serrations.
6. Apply Loctite 680 to face of rotor hub.
7. Slide second rotor set onto shaft aligning the locator slots and ridges. With the rotor set aligned, the magnets will repel one another. Hold the second set against the first until pressure is applied with the arbor press.
8. Press both rotor sets onto serrations.
9. Repeat procedures 6-8 until all sets are installed.

Design Considerations:

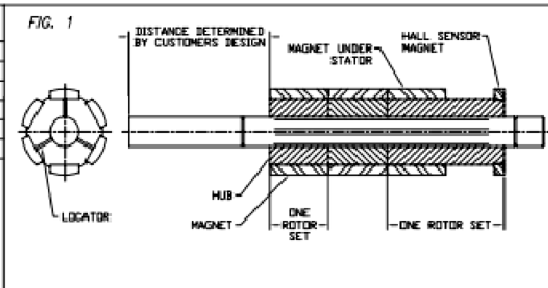
If possible, use nonmagnetic tooling to assemble rotors.
Shaft serrations are .001 - .003 over the finish shaft diameter.
Shafts must be surface or thru hardened to prevent hubs from scraping or peeling off serrations.
Serrations must be long enough to engage all hubs.

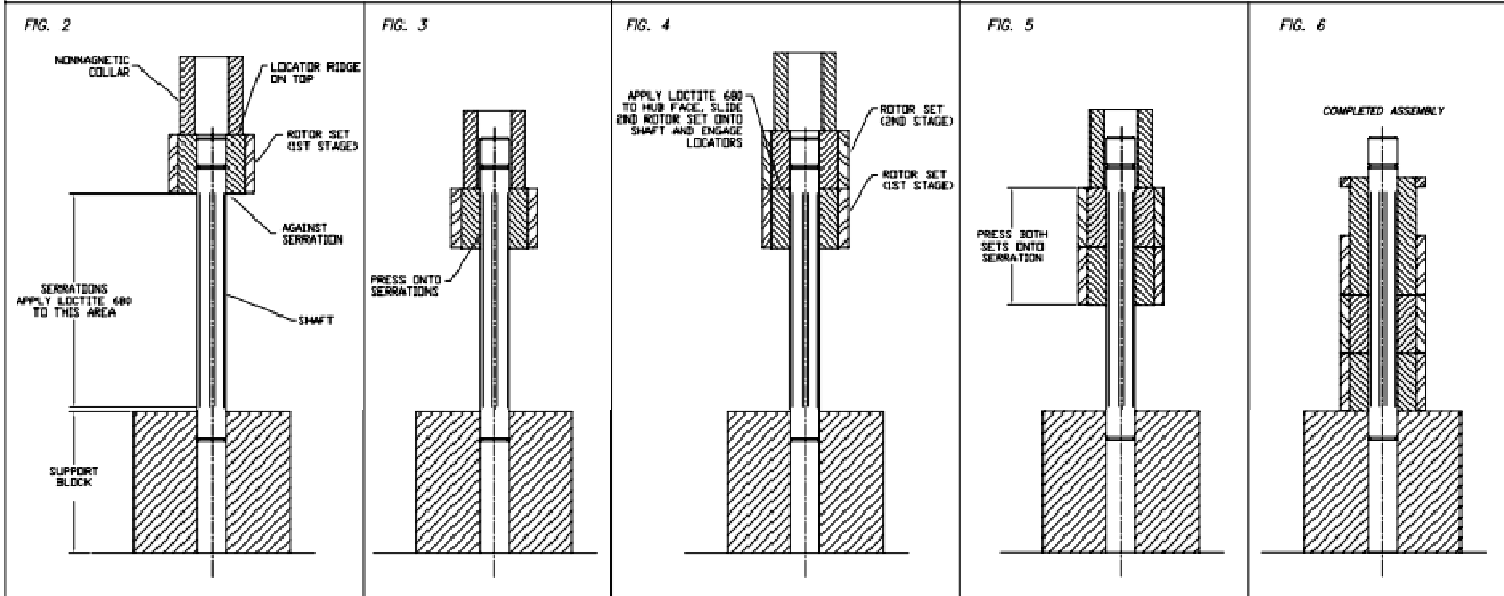
ROTOR HUB ASSEMBLY PROCEDURE
QB FRAMELESS MOTOR SERIES

CHART 1

MOTOR SERIES	NO. OF ROTOR SETS
1700, 2300, 3400	1
1701, 2301, 3401	2
1702, 2302, 3402	2
1703, 2303, 3403	3
1704, 2304, 3404	3

FIG. 1





Emoteq Corporation
10002-B East 43rd St. South
Tulsa, Oklahoma 74146
Tel: (918) 627-1845
Fax: (918) 660-0207
www.emoteq.com

Frameless motor mounting and installation.

Emoteq Corporation produces brushless DC motors in housed and frameless versions. This procedure provides guidelines for the mounting and installation of frameless motors.

Handling and Storage:
Handling and storage of motor components is very important. It is recommended that stators and rotors be stored in their original packaging until installation is required. Special care must be taken while handling stator assemblies. Damage to the coil insulation and lead wires can result in electrical shorts and possible electrical shocks. Precautions must also be taken while handling the rotor assembly, as strong magnet forces are present. Magnets can be chipped, cracked or broken if the rotor is dropped or large magnetic objects and other rotors are suddenly attracted to the rotor.

Description: Refer to Fig. 1 and Fig. 2.
Frameless motors are supplied as two separate components, stator assembly and rotor assembly. The stator assembly consists of a laminated stator core with powder coat insulation, magnet wire, slot wedge and 3 stator leads. Depending on the design and or customer preference the stator assembly may also contain 3 hall effect sensors with 5 leads and a thermistor or thermal switch. A circuit board containing the hall sensors and leads may be attached to the coil endturns. The rotor assembly consists of a magnetic rotor hub and magnets. The design may also require a nonmagnetic sleeve around the magnets in stainless steel, brass or fiberglass.

Fig. 1

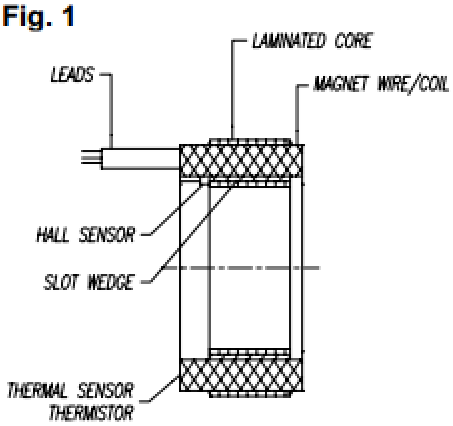
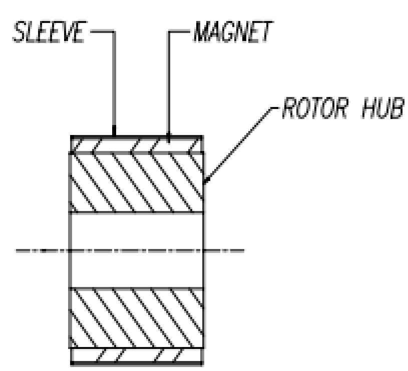


Fig. 2



Motor Design Layout: Refer to outline drawing and Fig. 3.

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www.emoteq.com

When laying out the motor design, refer to the mounting dimension on the outline drawing to ensure the rotor and stator are axially aligned. Rotor magnets are approximately .125" longer than the stator core length. The extra length is required to trigger the hall sensors. Maximum radial misalignment or concentricity between the rotor and stator is .004" TIR. (Total Indicator Reading). Angular misalignment will vary with the stator stack length. Refer to Fig. 3. Table 1. The size and application of the motor will dictate the type of bearings required. Consult bearing catalog or manufacture for the proper size and type.

Fig. 3

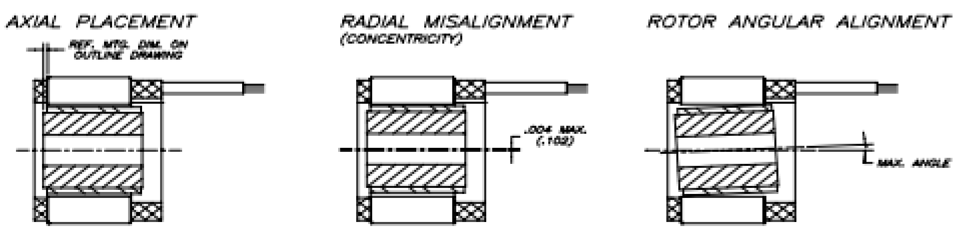

TABLE 1. ANGULAR ALIGNMENT	
STACK LENGTH	ANGLE
MIN. TO .650(16.5)	.3 DEG.
.651(16.53) TO 1.050(26.7)	.2 DEG.
1.051(26.7) TO 1.850(46.9)	.12 DEG.
OVER 1.851(47.0)	.07 DEG.

Stator Mounting: Refer to outline drawing and Fig. 4.

Allied Motion
EMOTEQ

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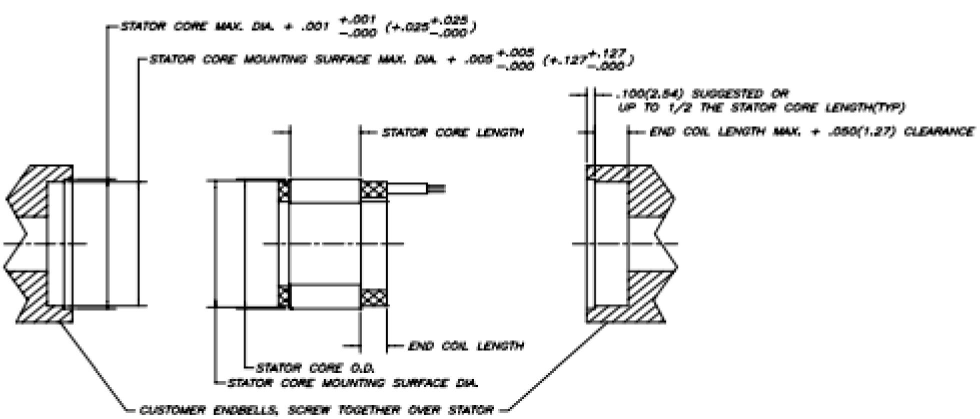
The stator assembly is designed to mount between two endbells. Endbells can be produced by either machining a solid piece of stock or through a die-casting process. In either case the endbells must be designed to provide a rigid and stable support for the stator and rotor assembly. Stators are supplied with a mounting surface machined on each end of the stator core. The mounting surface on the endbell must be designed to the following criteria. The outside diameter of the endbell shoulder is equal to the maximum stator OD + .001" +.001"/-.000". The inside diameter of the shoulder is equal to the max. stator core mounting diameter + .005" +.005"/-.000". The depth of the shoulder is suggested at .100" min. up to ½ the stator core length. A clearance gap of .050" minimum must be provided between the end coils and the endbell wall. A greater clearance gap will provide easier installation of the lead wires and may be necessary depending on lead wire exit. A grommet/strain relief should be used at the lead exit to protect lead insulation from chafing and protect leads from any tensile forces.

Fig. 4



Rotor Mounting: Refer to outline drawing and Fig. 5.
Rotors can be mounted to shafts by various methods. Clamp, bond and press will be addressed in this procedure. The rotor ID is manufactured per the customer specification or to the standard catalog diameter. The shaft diameter for each method is equal to the rotor ID - .001". Clearance range between shaft and rotor should be .0002" min. to .002 max.

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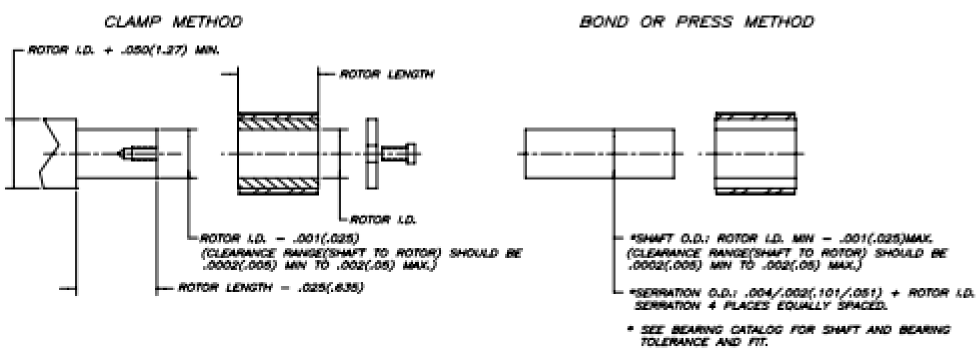
www.emoteq.com

Clamp Method:
This method involves holding the rotor to the shaft with force exerted thru a thrust disc and machine screw. A lock washer or bonding agent can be applied to prevent the screw from becoming loose. The number of screws will depend on the size of the rotor, torque requirements and customer application. Applications involving high torque or sudden start and stop modes may require a woodruff key or square key along with the clamp.

Bond Method:
This method involves holding the rotor to the shaft with a high strength retaining compound. Adhesive manufacturers produce retaining compounds specifically for this design and should be consulted to help select the correct retaining compound for your application.

Press Method:
This method involves holding the rotor to the shaft with an interference fit between a set of serrations on the shaft and the rotor ID. A set of 4 serrations equally spaced around the outside diameter of the shaft is required. The diameter over the serrations is equal to the rotor ID + .002 +/-.001". Serration length should be no less than ¾ the length of the rotor. A tapered serration is acceptable.

Fig. 5



Assembly:
Small motors (less than 4" OD) can usually be assembled by hand. Careful attention must be taken while inserting the rotor assembly thru the stator. Damage to the stator coil and magnets can occur if the magnet forces suddenly pull the rotor into the stator. The rotor assembly must be securely supported by hand during this process.
For large motors, assembly fixtures are recommended to support the stator and rotor during insertion of the rotor assembly.

Appendix E

Hazard Identification Checklist

ME428/429/430 Senior Design Project 2014-2015

SENIOR PROJECT CONCEPT DESIGN HAZARD IDENTIFICATION CHECKLIST

Team: LOW-COST SUBMERSIBLE THRUSTER Advisor: FABIJANIC

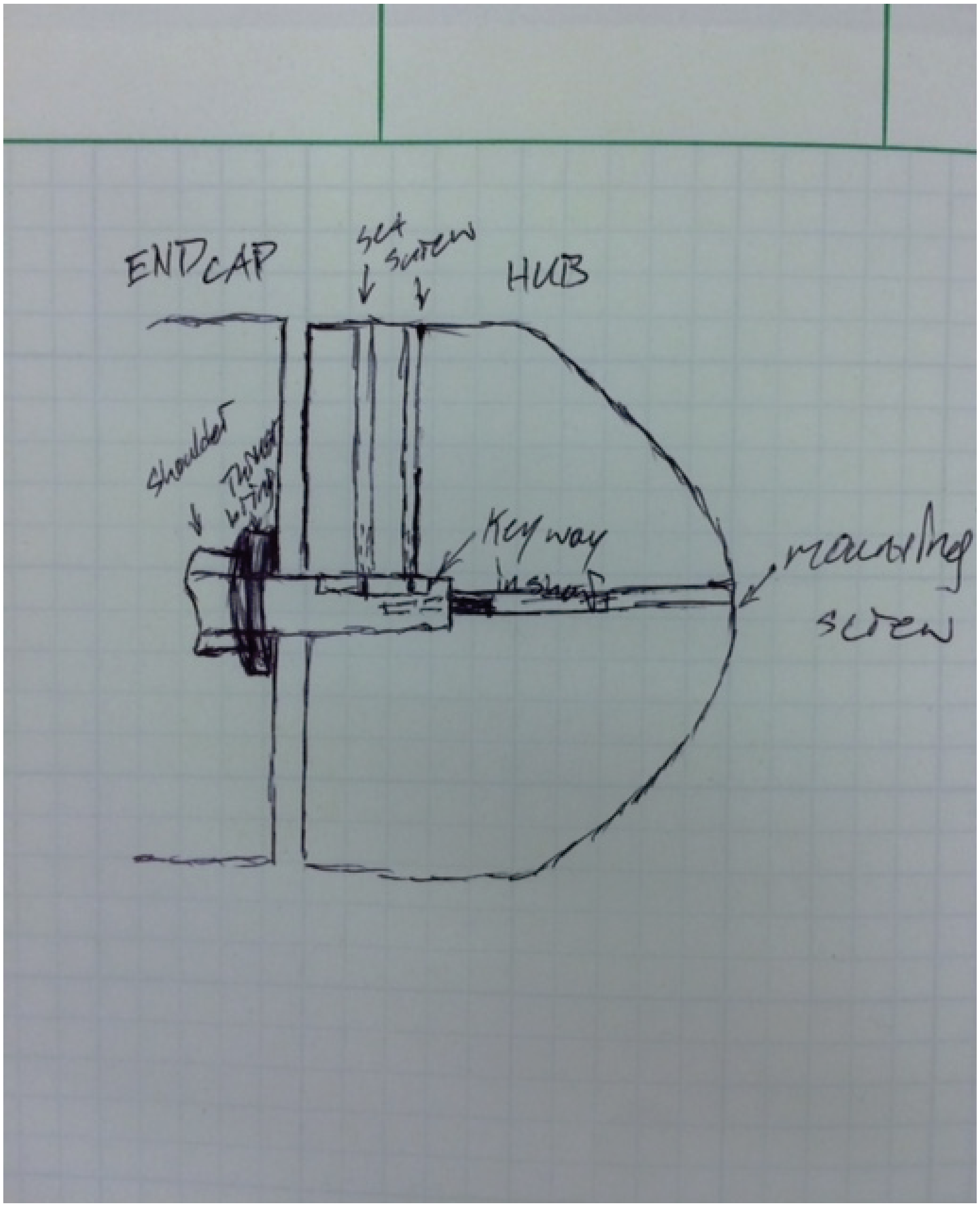
Y	N	
☑	☐	Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
☑	☐	Can any part of the design undergo high accelerations/decelerations?
☑	☐	Will the system have any large moving masses or large forces?
☐	☑	Will the system produce a projectile?
☐	☑	Would it be possible for the system to fall under gravity creating injury?
☐	☑	Will a user be exposed to overhanging weights as part of the design?
☑	☐	Will the system have any sharp edges?
☐	☑	Will any part of the electrical systems not be grounded?
☑	☐	Will there be any large batteries or electrical voltage in the system above 40 V either AC or DC?
☑	☐	Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
☐	☑	Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
☐	☑	Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
☐	☑	Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
☑	☐	Can the system generate high levels of noise?
☑	☐	Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
☑	☐	Is it possible for the system to be used in an unsafe manner?
☐	☑	Will there be any other potential hazards not listed above? If yes, please explain on reverse.

For any "Y" responses, add a complete description, list of corrective actions to be taken, and dates to be completed on the reverse side.

Description of Hazard	Corrective Actions to be Taken	Planned Completion Date	Actual Completion Date
SHARP PROPELLER WILL ROTATE AT HIGH SPEEDS, CREATE HARMFUL CONTACT POINTS	SHROUD THE PROPELLER TO LIMIT CONTACT POINTS ON SIDE OF PROPELLER, INSTRUCT PERSONNEL ON SAFE HANDLING PROCEDURES	1 FEB 2015	
150 V BATTERIES ON-BOARD SYSTEM	INSULATE ELECTRONIC SYSTEMS IN EPOXY.	18 MAR 2015	
MOTOR CAN POTENTIALLY GENERATE HIGH LEVELS OF NOISE.	INSTRUCT PERSONNEL TO WEAR EARPLUGS IF NOISE LEVEL IS UNCOMFORTABLE.	1 FEB 2015	
DEVICE WILL OPERATE AT DEPTHS ~1000 ft.	INSULATE ELECTRONIC SYSTEMS IN EPOXY TO PROTECT USERS FROM POTENTIAL SHOCK.	18 MAR 2015	

Appendix F

Stress Analysis/Sketches



Longitudinal stress for housing centerpiece 1/27/15

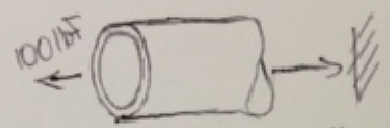
~~$\sigma = \frac{Pd}{4t}$~~

~~P = Pressure~~

~~d = mean Ø~~

~~t = thickness~~

~~100 lbf~~



stress ⇒ $\sigma_a = \frac{100\text{ lb}}{\pi(r_o^2 - r_i^2)}$

~~$\sigma_a = \frac{100\text{ lb}}{\pi\left(r_o^2 - \left(\frac{3.25}{2}\right)^2 in^2\right)}$~~

~~$40000\text{ psi}\,(\pi)/100\text{ lb} + \left(\frac{3.25}{2}\right) in^2 = r_o^2$~~

~~steel~~ alluminum 6061-T6 has tensile strength of

$\sigma_{all} = 40000$ psi

with a wall thickness of 1/4"

$$\sigma = \frac{100\text{ lb}}{\pi\left(\left(\frac{3.75}{2}\right)^2 - \left(\frac{3.25}{2}\right)^2\right) in^2} = 36.38\text{ psi}$$

$$\text{F.S. of } \frac{40000\text{ psi}}{36.38\text{ psi}} = 1099 \Rightarrow \text{no chance of fail}$$

* Driving factor is bolts. Bolts must not strip and must fit (tap) into housing

Bolt Analysis 1/28/15 (Preload)

1/8" OD $A_b = \pi(1/8/2)^2 = .012 in^2$

σ in bolt $= \frac{F}{A} = \frac{33.33\text{ lb}}{.012 in^2}$ ~~= 2715 psi.~~

This is major Ø for minor Ø → $= \frac{F}{A} = \frac{33.33\text{ lb}}{.00716 in^2} = 4655$ psi

F.O.S = 15

T to achieve preload $= K F_i d = .2(2715\text{ psi})(1/8")$

eq. 8-27 pg 440 Shigley's

$\boxed{= 67.88\text{ lb·in}}$ T required (preload)

Screw Strength Analysis 1/29/15

END CAP – HOUSING SCREWS

$L_e = 2(A_t)/[.5(\pi)(D-.64952p)]$

$A_t = \frac{\pi}{4}(D-.938194p)^2$

$A_t = \frac{\pi}{4}(.175-.938194(1/40))^2$

$A_t = .0081 in^2$

$L_e = 2(.0081 in^2)/[.5(\pi)(.175-.64952(1/40))]$

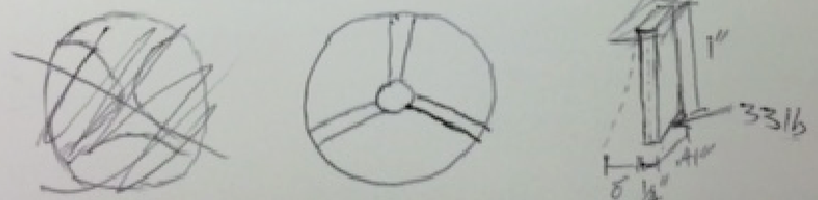
$L_e = .0948 in$ ⇒ length of thread engagement needed so screw threads dont pull out.

To account for a female mate,

$Le_2 = 2L_e = .1896 in$ ⇒ $3/16 in$ ≈ 8 threads must be in contact

F.O.S = 5.3

FRONT END CAP STRENGTH ANALYSIS 1/29/15



~~$\sigma = \frac{PL}{AE} = \frac{33.33(1 in)}{.1025 in^2(10\times10^6 psi)}$~~

$\delta = \frac{PL^3}{3EI} = \frac{33.33(1 in)^3}{3(10\times10^6 \frac{lb}{in^2})(\frac{1}{12}(.41)(.25)^3)}$ $\delta = .002 in$ ✓ very conservative and still good

$\sigma = \frac{My}{I} = \frac{33 lb(1 in)(1/8 in)}{\frac{1}{12}(.41)(.25)^3} = 7726 psi$ F.S. = 8

Bolt analysis cont. 1/28/13 (Preload available)

Table 8-2 shigley's

minor Ø = .00716 ~~mean Ø = .125 + .00716 / 2 = .06608 in~~

~~$\lambda = \tan^{-1}\left(\frac{1}{\pi d_m}\right) = \frac{1}{\pi(.06608 in)} =$~~

~~$\lambda = 78.27^\circ$~~

minor Ø Area = .00716 in²

d_r = minor Ø = $\sqrt{4(.00716)/\pi}$ = .0954

mean Ø = $\frac{.125 + .0954}{2}$ = .11 in

for fine threaded

$l = \frac{1 in}{44 thread - 1} = .02$

$\lambda = \tan^{-1}\left(\frac{l}{\pi d_m}\right)$

$\lambda = \tan^{-1}\left(\frac{.0232 in}{\pi(.11 in)}\right)$

$\lambda = 3.85^\circ$

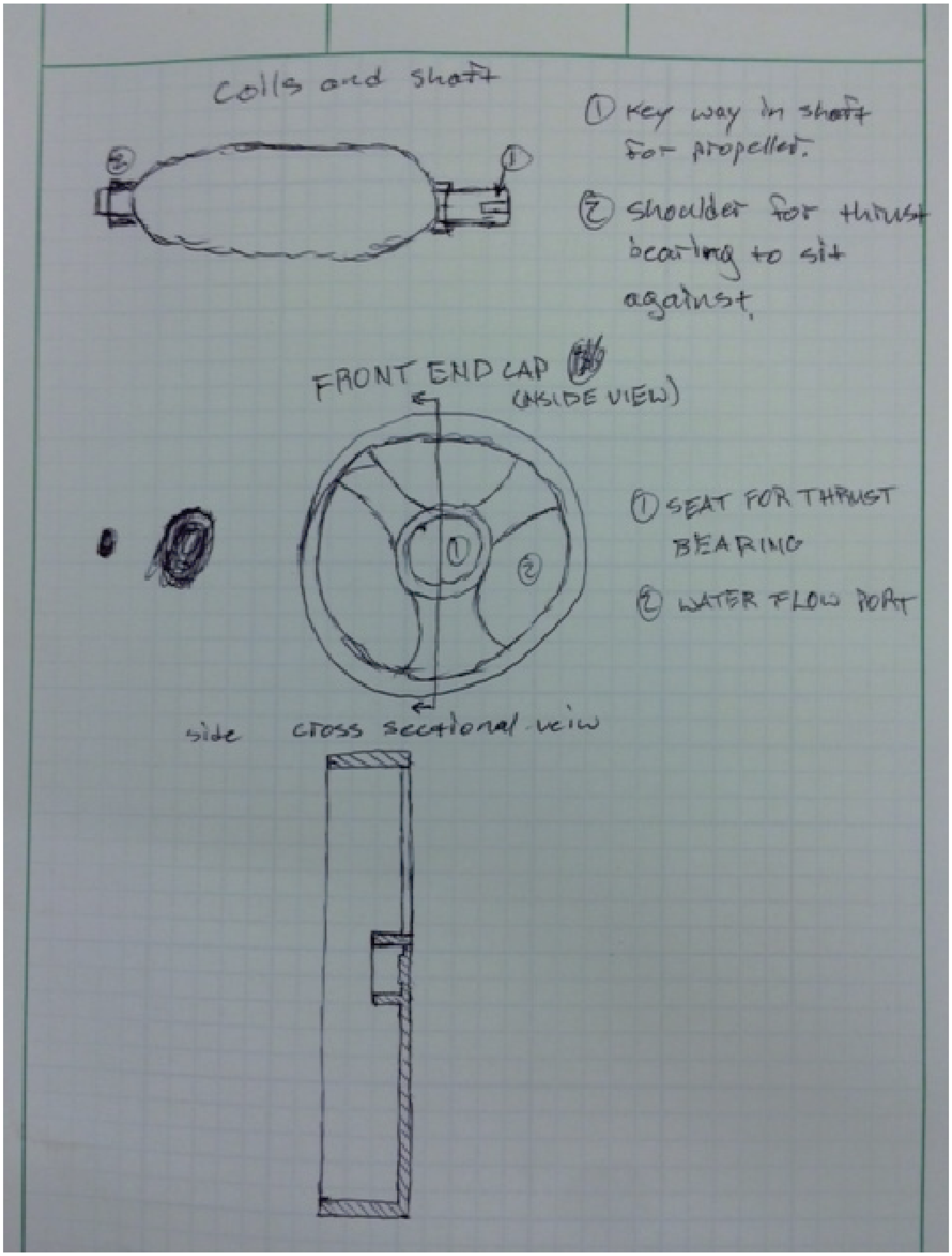
$\alpha = 30^\circ$

$T_{available} = \left[\frac{d_m}{2d}\left(\frac{\tan\lambda + f\sec\alpha}{1 - f\tan\lambda\sec\alpha}\right) + .625 f_c\right] F_i d$

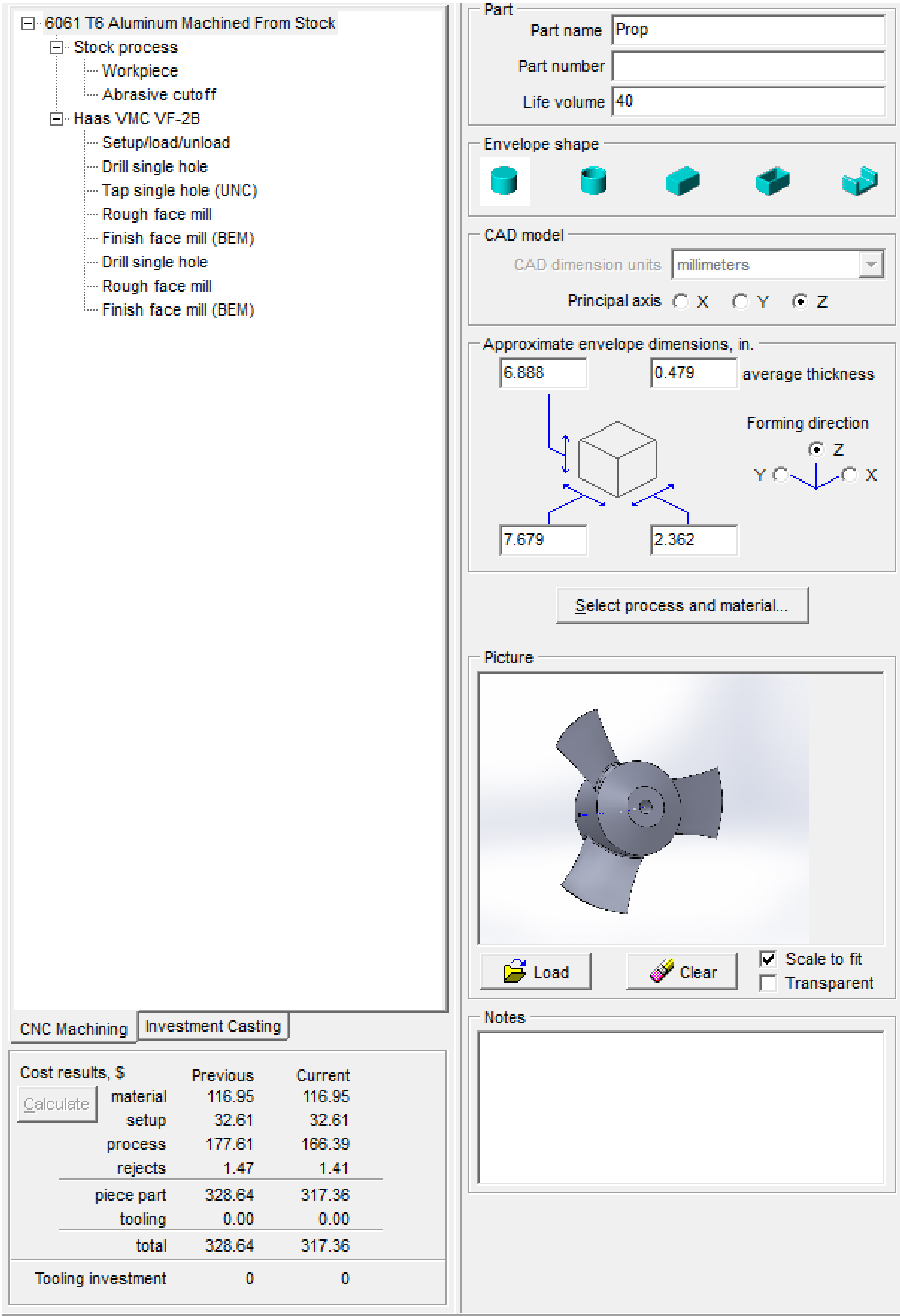
$T_{avail} = \left[\frac{.0954}{2(.125)}\left(\frac{\tan(3.85) + .15\sec(30)}{1 - .15\tan(3.85)\sec(30)}\right) + 6.25(.15)\right] 4655 psi(.125 in)$

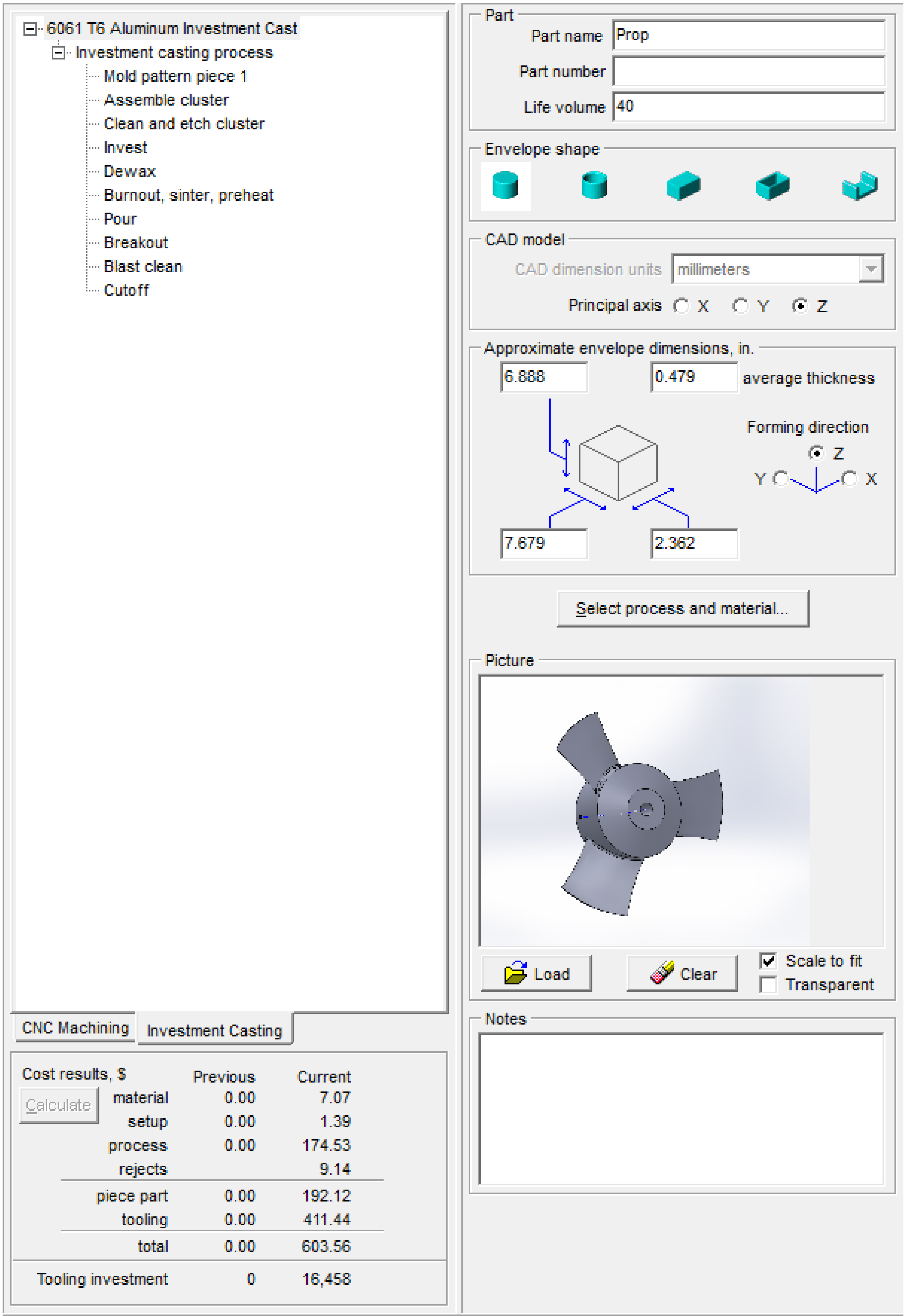
$= (.3816(.2433) + .9375)\, 581.88$ lb in

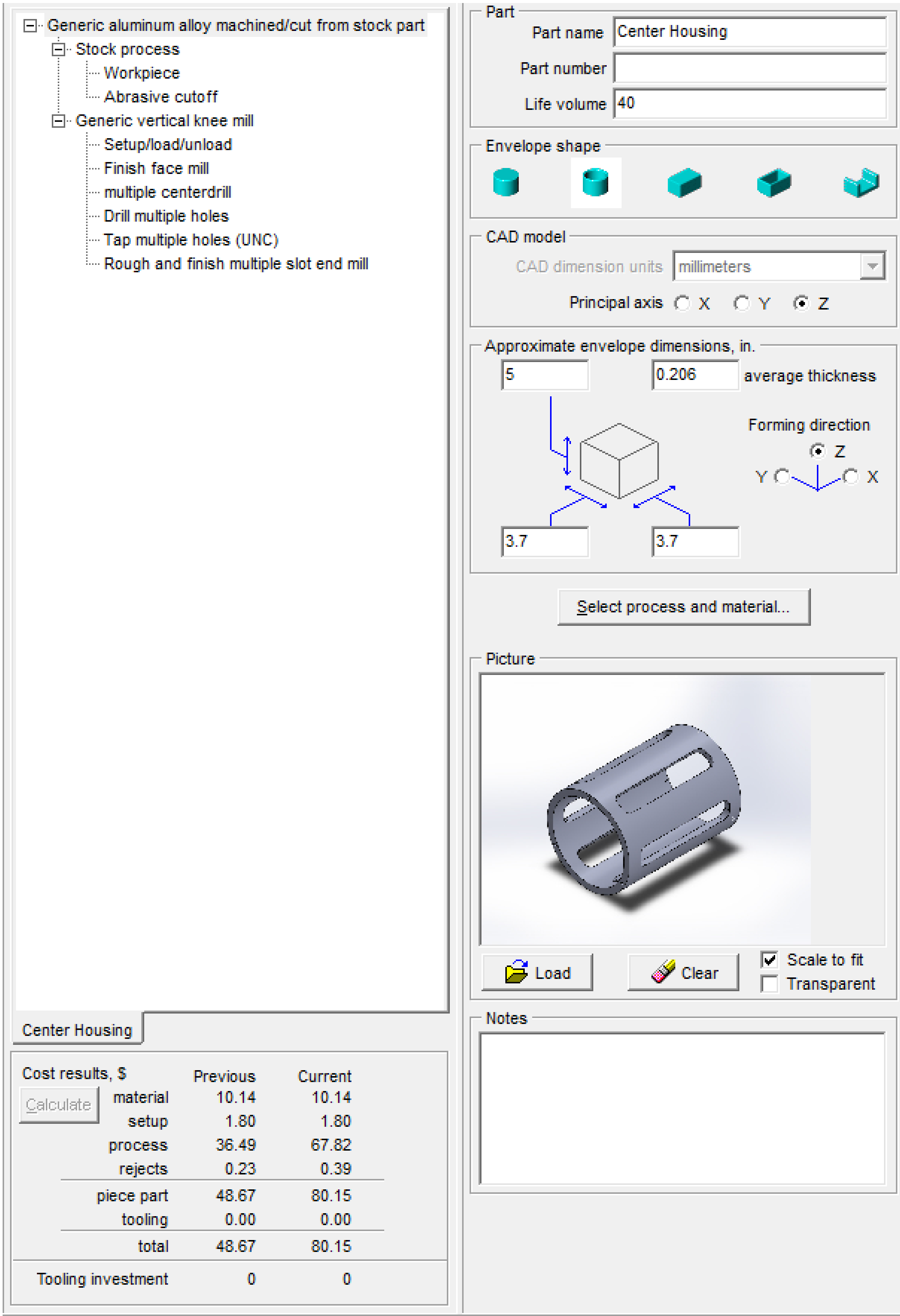
$\boxed{= 599.54 \text{ lb in}}$ $T_{available}$ for preload

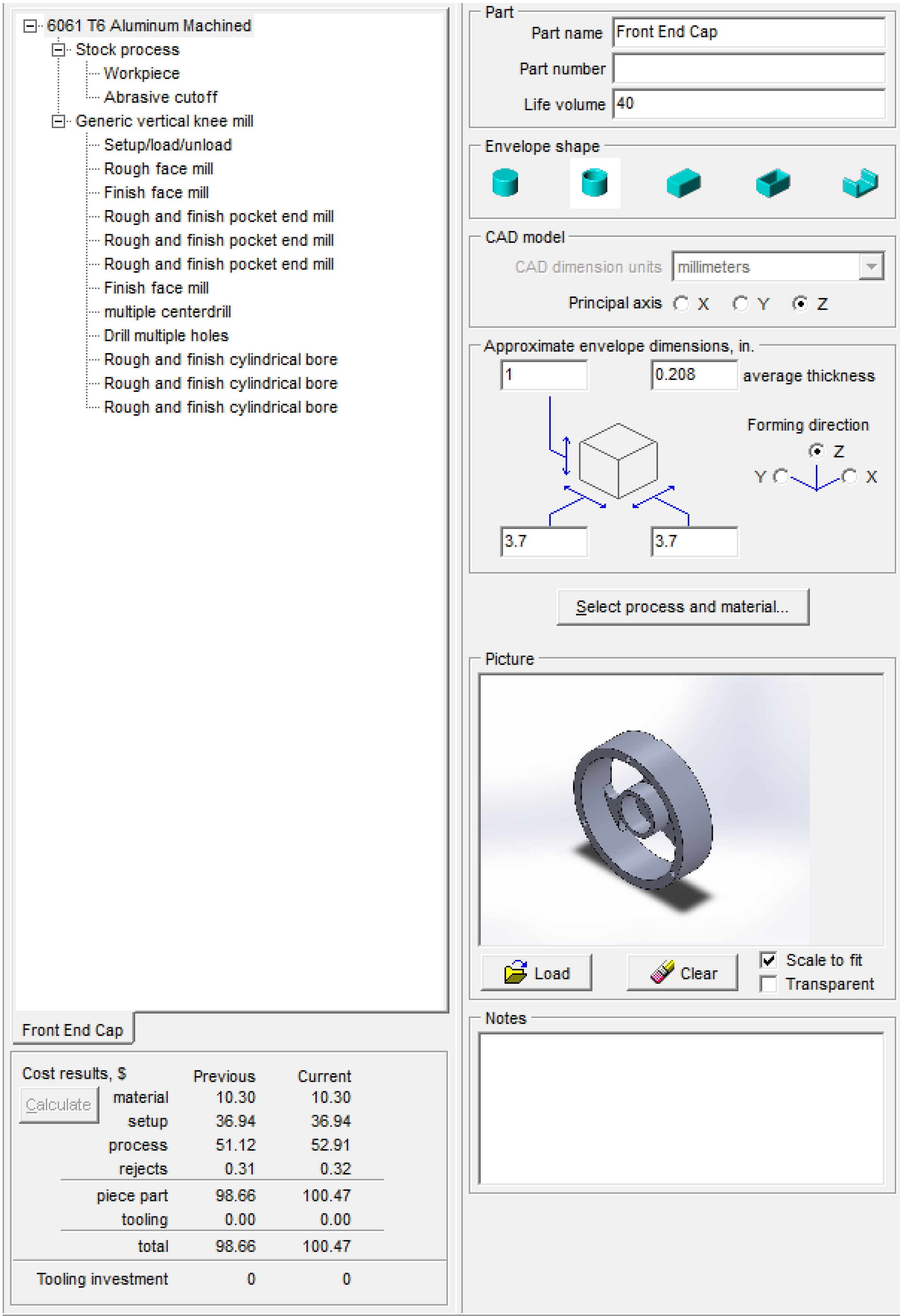

Coils and shaft
① Key way in shaft for propeller.
② shoulder for thrust bearing to sit against.
FRONT END CAP
(INSIDE VIEW)
① SEAT FOR THRUST BEARING
② WATER FLOW PORT
side
cross sectional veiw

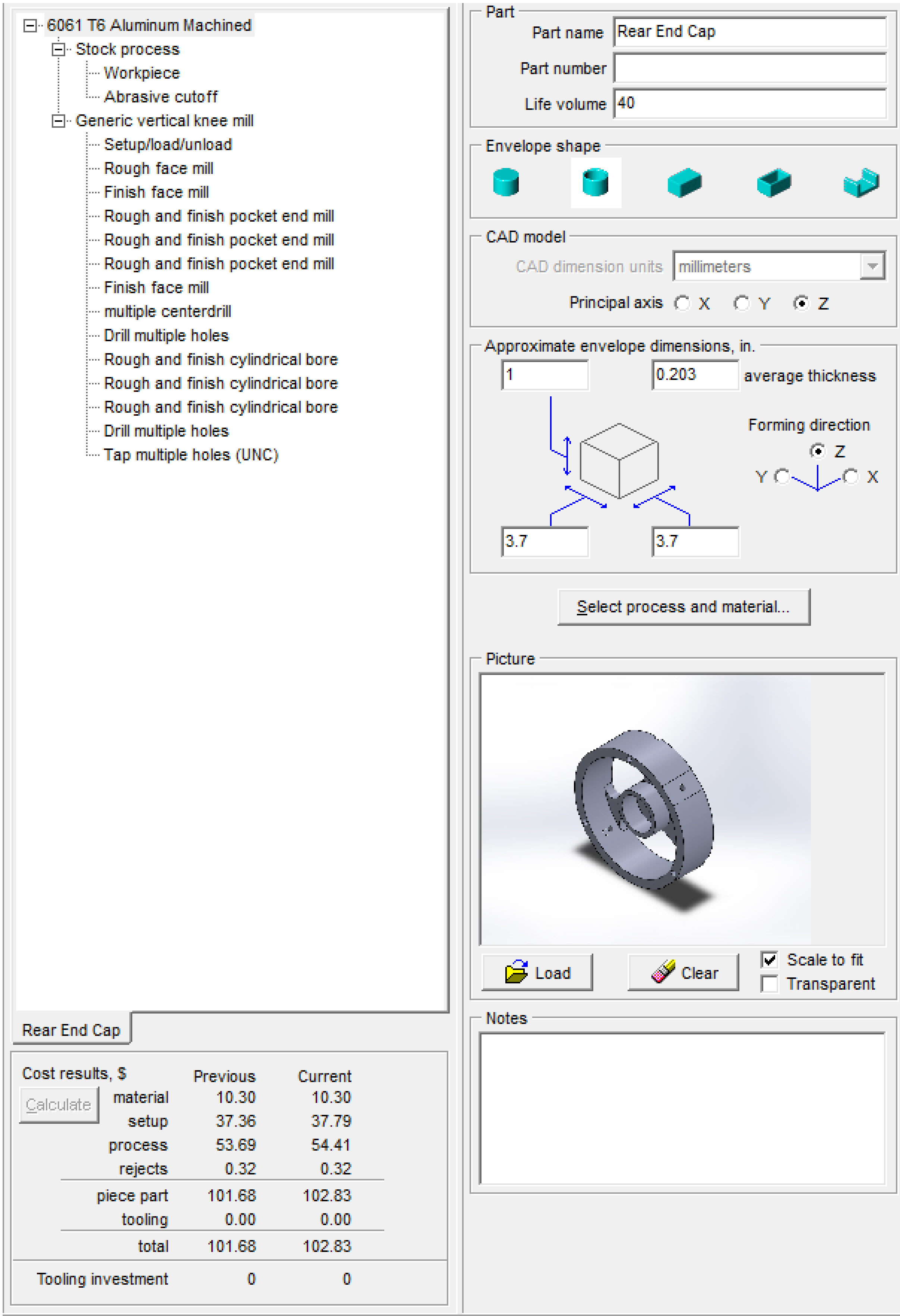
Appendix G


6061 T6 Aluminum Machined From Stock
Stock process
Workpiece
Abrasive cutoff
Haas VMC VF-2B
Setup/load/unload
Drill single hole
Tap single hole (UNC)
Rough face mill
Finish face mill (BEM)
Drill single hole
Rough face mill
Finish face mill (BEM)
CNC Machining
Investment Casting
Cost results, $
Calculate
Previous
Current
material 116.95 116.95
setup 32.61 32.61
process 177.61 166.39
rejects 1.47 1.41
piece part 328.64 317.36
tooling 0.00 0.00
total 328.64 317.36
Tooling investment 0 0
Part
Part name
Prop
Part number
Life volume
40
Envelope shape
CAD model
CAD dimension units
millimeters
Principal axis
X
Y
Z
Approximate envelope dimensions, in.
6.888
0.479
average thickness
Forming direction
Z
Y
X
7.679
2.362
Select process and material...
Picture
Load
Clear
Scale to fit
Transparent
Notes


6061 T6 Aluminum Investment Cast
Investment casting process
Mold pattern piece 1
Assemble cluster
Clean and etch cluster
Invest
Dewax
Burnout, sinter, preheat
Pour
Breakout
Blast clean
Cutoff
CNC Machining
Investment Casting
Cost results, $
Previous
Current
Calculate
material 0.00 7.07
setup 0.00 1.39
process 0.00 174.53
rejects 9.14
piece part 0.00 192.12
tooling 0.00 411.44
total 0.00 603.56
Tooling investment 0 16,458
Part
Part name
Prop
Part number
Life volume
40
Envelope shape
CAD model
CAD dimension units
millimeters
Principal axis
X
Y
Z
Approximate envelope dimensions, in.
6.888
0.479
average thickness
Forming direction
Z
Y
X
7.679
2.362
Select process and material...
Picture
Load
Clear
Scale to fit
Transparent
Notes

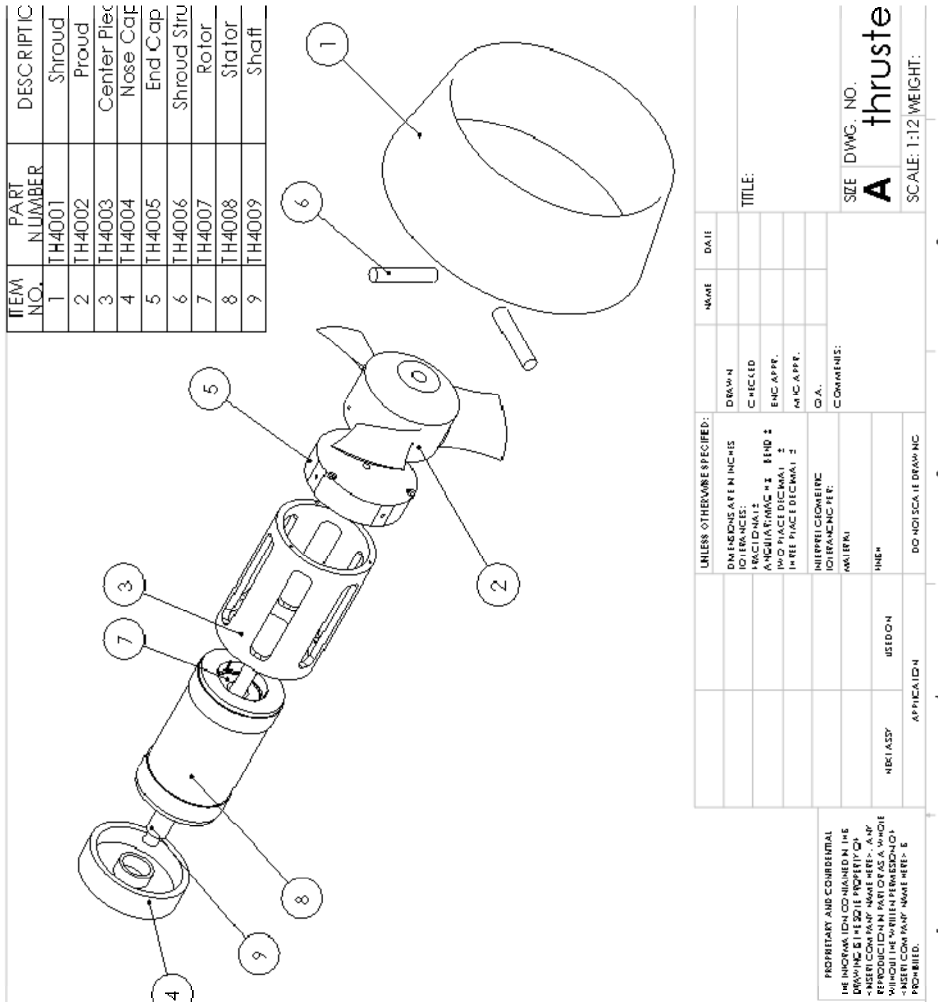

Generic aluminum alloy machined/cut from stock part
Stock process
Workpiece
Abrasive cutoff
Generic vertical knee mill
Setup/load/unload
Finish face mill
multiple centerdrill
Drill multiple holes
Tap multiple holes (UNC)
Rough and finish multiple slot end mill
Center Housing
Cost results, $
Previous
Current
Calculate
material 10.14 10.14
setup 1.80 1.80
process 36.49 67.82
rejects 0.23 0.39
piece part 48.67 80.15
tooling 0.00 0.00
total 48.67 80.15
Tooling investment 0 0
Part
Part name
Center Housing
Part number
Life volume
40
Envelope shape
CAD model
CAD dimension units
millimeters
Principal axis
X
Y
Z
Approximate envelope dimensions, in.
5
0.206
average thickness
Forming direction
Z
Y
X
3.7
3.7
Select process and material...
Picture
Load
Clear
Scale to fit
Transparent
Notes

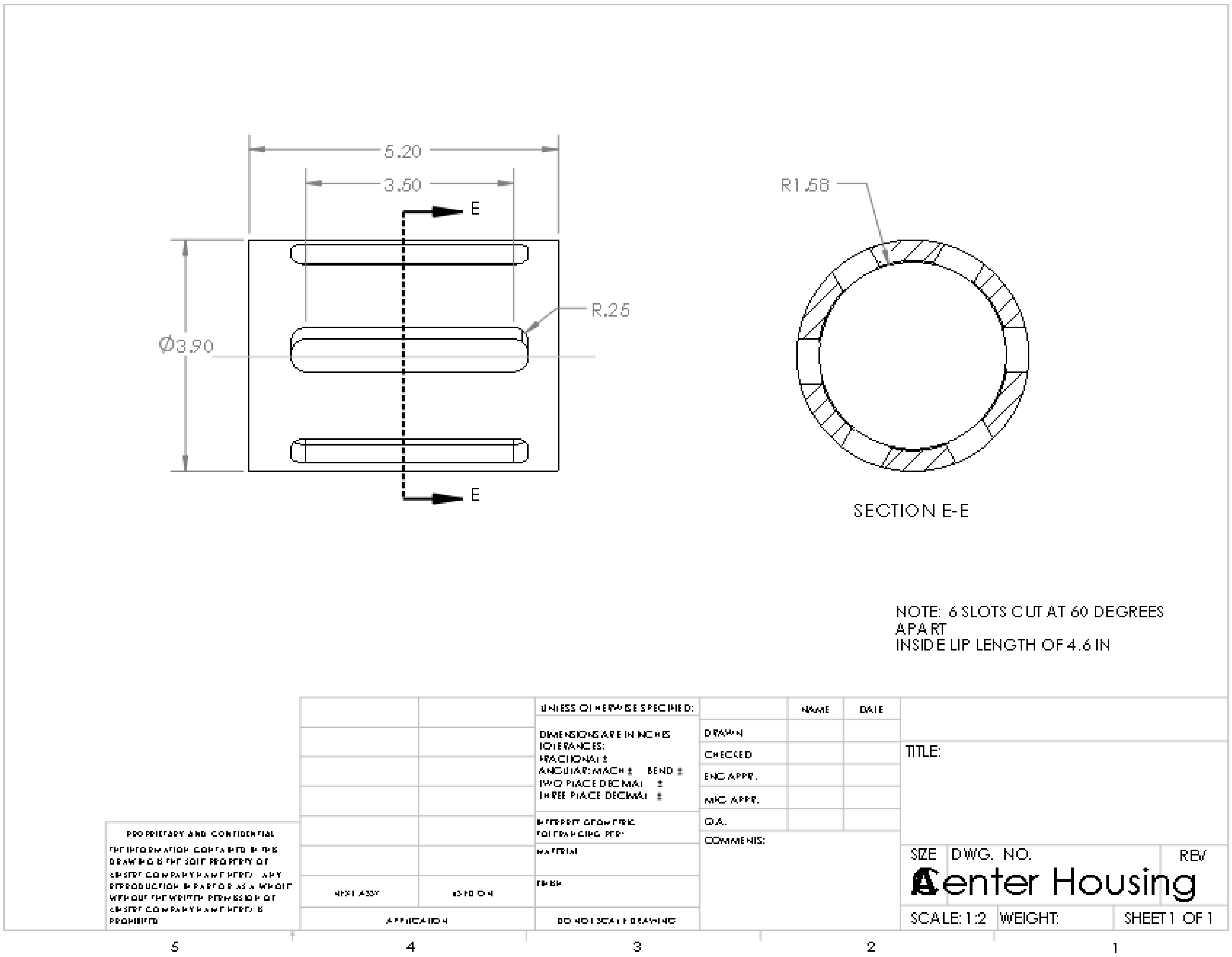

6061 T6 Aluminum Machined
Stock process
Workpiece
Abrasive cutoff
Generic vertical knee mill
Setup/load/unload
Rough face mill
Finish face mill
Rough and finish pocket end mill
Rough and finish pocket end mill
Rough and finish pocket end mill
Finish face mill
multiple centerdrill
Drill multiple holes
Rough and finish cylindrical bore
Rough and finish cylindrical bore
Rough and finish cylindrical bore
Front End Cap
Cost results, $
Previous
Current
Calculate
material 10.30 10.30
setup 36.94 36.94
process 51.12 52.91
rejects 0.31 0.32
piece part 98.66 100.47
tooling 0.00 0.00
total 98.66 100.47
Tooling investment 0 0
Part
Part name
Front End Cap
Part number
Life volume
40
Envelope shape
CAD model
CAD dimension units
millimeters
Principal axis X Y Z
Approximate envelope dimensions, in.
1
0.208
average thickness
Forming direction
Z
Y
X
3.7
3.7
Select process and material...
Picture
Load
Clear
Scale to fit
Transparent
Notes

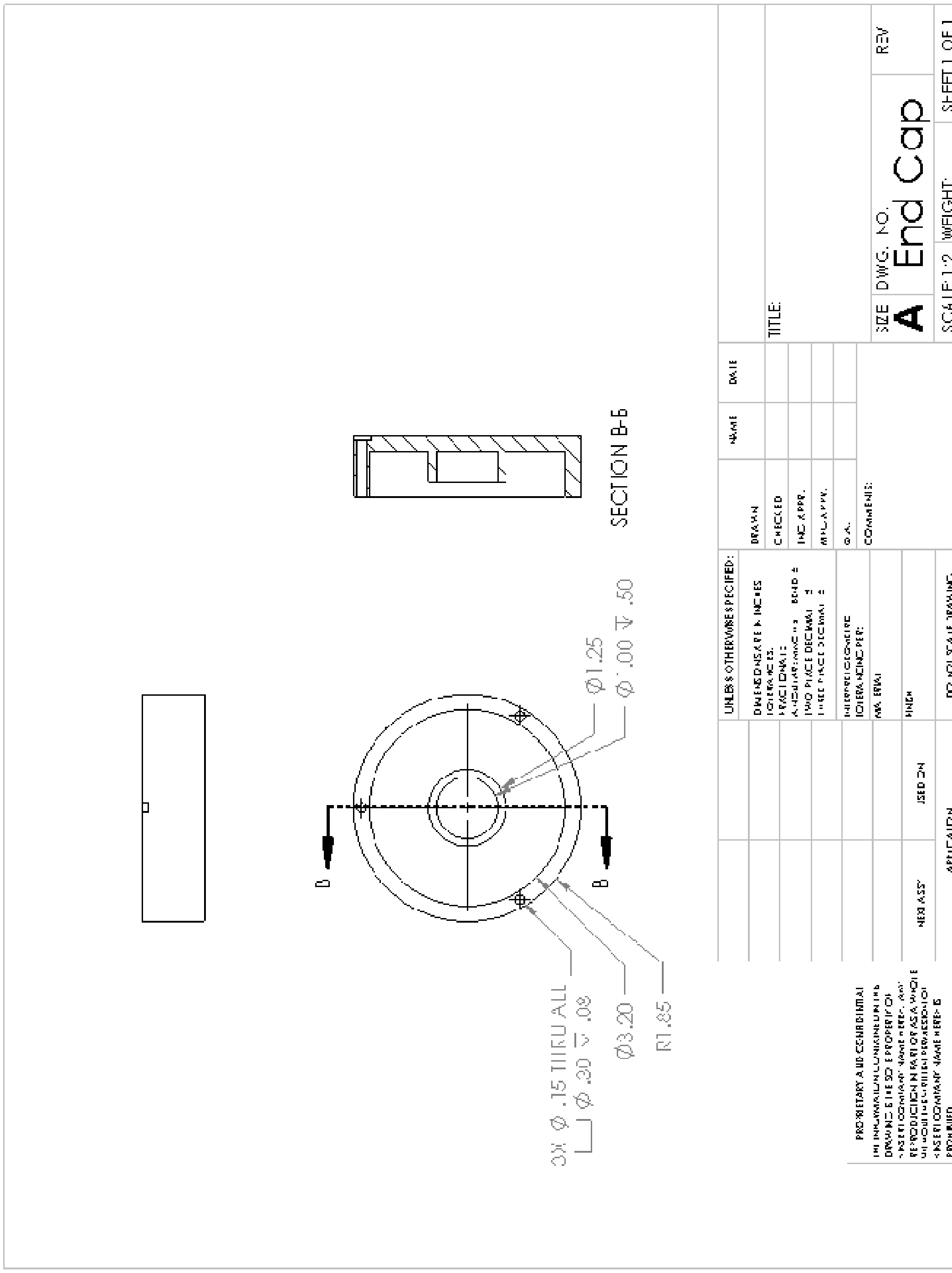

6061 T6 Aluminum Machined
Stock process
Workpiece
Abrasive cutoff
Generic vertical knee mill
Setup/load/unload
Rough face mill
Finish face mill
Rough and finish pocket end mill
Rough and finish pocket end mill
Rough and finish pocket end mill
Finish face mill
multiple centerdrill
Drill multiple holes
Rough and finish cylindrical bore
Rough and finish cylindrical bore
Rough and finish cylindrical bore
Drill multiple holes
Tap multiple holes (UNC)
Rear End Cap
Cost results, $
Previous
Current
Calculate
material 10.30 10.30
setup 37.36 37.79
process 53.69 54.41
rejects 0.32 0.32
piece part 101.68 102.83
tooling 0.00 0.00
total 101.68 102.83
Tooling investment 0 0
Part
Part name Rear End Cap
Part number
Life volume 40
Envelope shape
CAD model
CAD dimension units millimeters
Principal axis X Y Z
Approximate envelope dimensions, in.
1
0.203 average thickness
Forming direction
Z
Y X
3.7
3.7
Select process and material...
Picture
Load
Clear
Scale to fit
Transparent
Notes

Appendix H

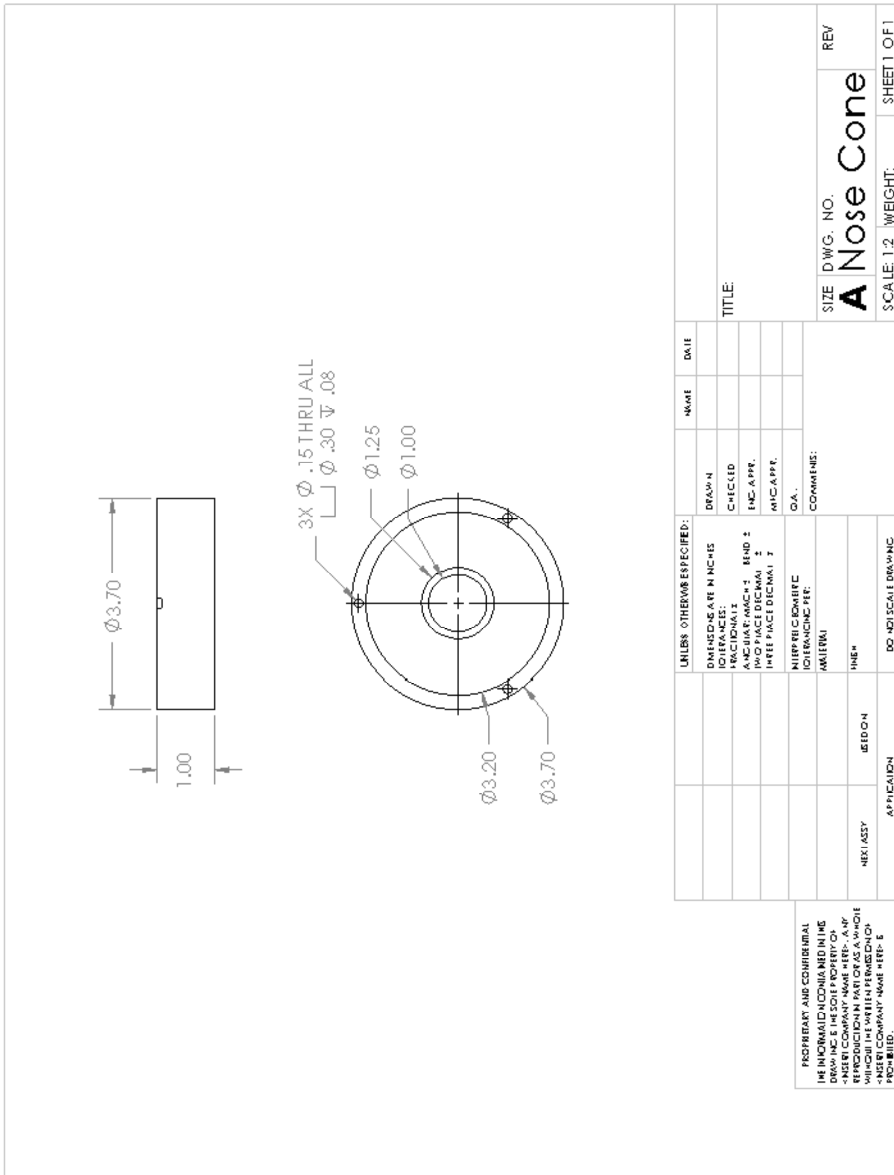
Thruster Bill of Materials/Machine Drawings

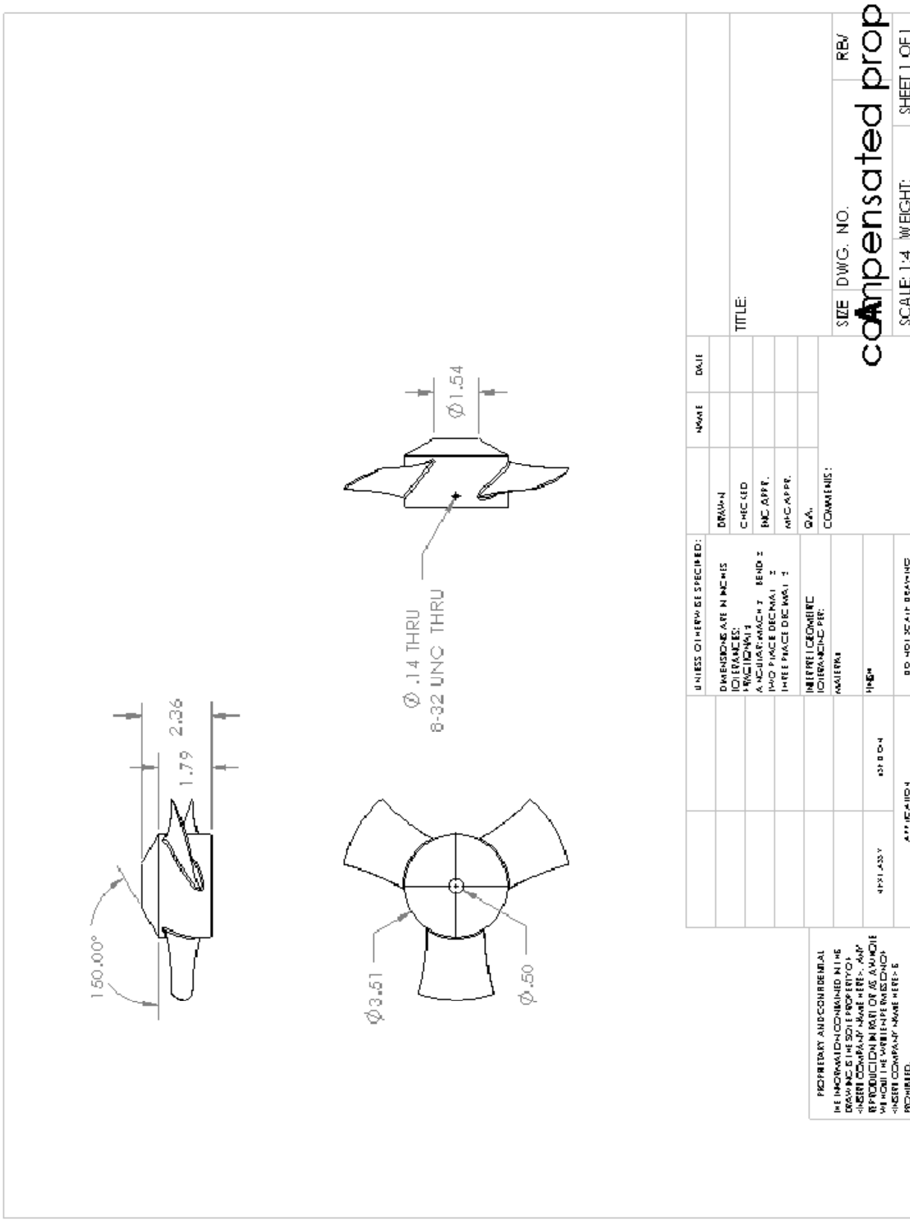



5.20
3.50
E
E
R.25
Ø3.90
R1.58
SECTION E-E
NOTE: 6 SLOTS CUT AT 60 DEGREES
APART
INSIDE LIP LENGTH OF 4.6 IN
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
PROPRIETARY AND CONFIDENTIAL
NEXT ASSY
USED ON
APPLICATION
MATERIAL
FINISH
DO NOT SCALE DRAWING
SIZE
DWG. NO.
REV
A
Center Housing
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1



3X Ø .15 THRU ALL
Ø .30 ▽ .08
Ø3.20
R1.85
Ø1.25
Ø1.00 ▽ .50
B
B
SECTION B-B
UNLESS OTHERWISE SPECIFIED:
DRAWN
CHECKED
NAME
DATE
COMMENTS:
TITLE:
SIZE
A
DWG. NO.
End Cap
REV
SCALE 1:2
WEIGHT:
SHEET 1 OF 1


Ø3.70
1.00
3X Ø .15 THRU ALL
Ø .30 ↧ .08
Ø1.25
Ø1.00
Ø3.20
Ø3.70
UNLESS OTHERWISE SPECIFIED:
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
TITLE:
SIZE
DWG. NO.
A
Nose Cone
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
PROPRIETARY AND CONFIDENTIAL


150.00°
1.79
2.36
Ø .14 THRU
8-32 UNC THRU
Ø1.54
Ø3.51
Ø.50
UNLESS OTHERWISE SPECIFIED:
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
SIZE
A
DWG. NO.
compensated prop
REV
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1
DO NOT SCALE DRAWING
PROPRIETARY AND CONFIDENTIAL

Appendix I

Open Prop Design Parameters

OpenProp Performance Table

Date and time: 2015-01-28 16:17:58

r/R	V*	beta	betai	Gamma	CL	Sigma	dBetai
0.476	13.23	22.04	28.95	0.1589	0.397	1.463	10.65
0.531	14.59	19.94	26.28	0.1613	0.377	1.202	10.02
0.587	15.92	18.20	24.23	0.1653	0.356	1.008	9.39
0.642	17.29	16.72	22.43	0.1693	0.335	0.855	8.82
0.697	18.67	15.47	20.85	0.1729	0.314	0.733	8.30
0.752	20.05	14.38	19.48	0.1762	0.293	0.635	7.83
0.807	21.44	13.44	18.29	0.1792	0.273	0.555	7.40
0.862	22.83	12.60	17.25	0.1816	0.252	0.489	7.01
0.917	24.22	11.87	16.32	0.1833	0.231	0.435	6.65
0.972	25.65	11.21	15.34	0.1834	0.211	0.387	6.33

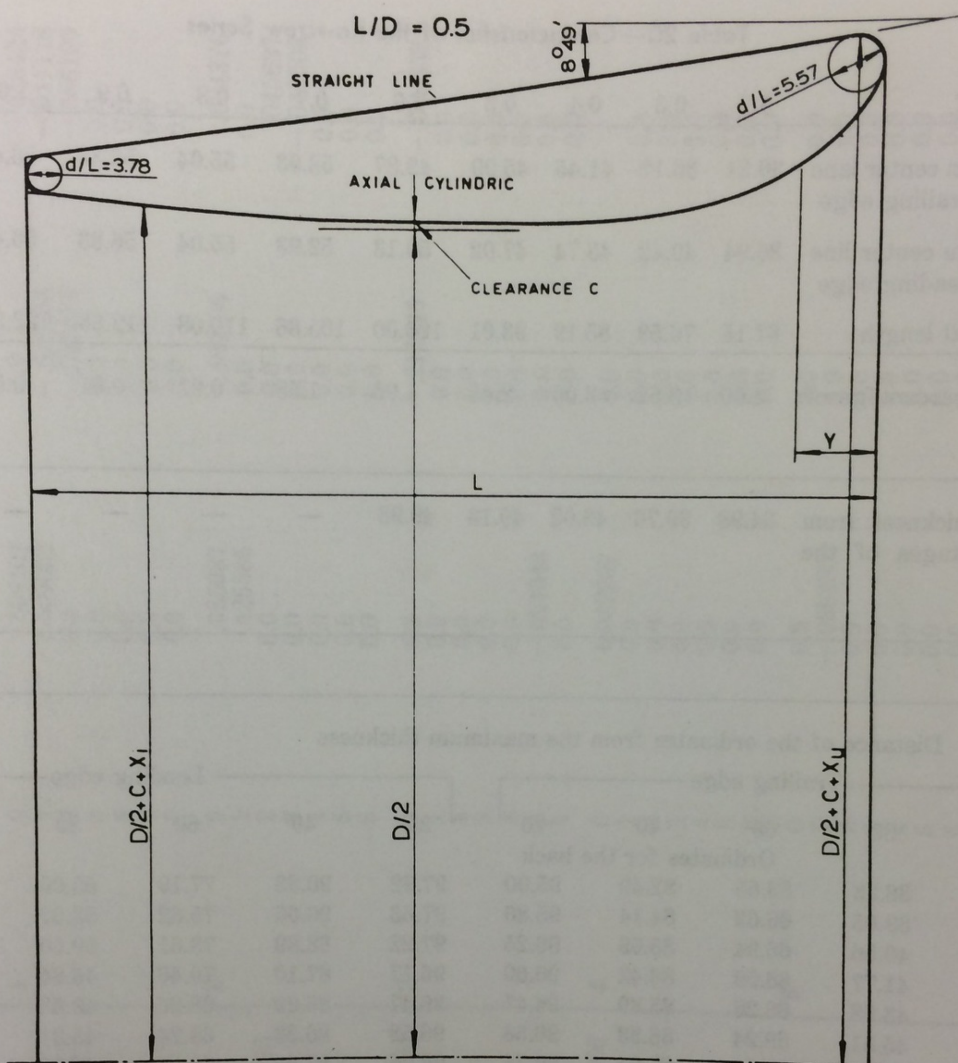
```
r/R       [ ], radial position of control points / propeller radius.
V*        [m/s], total inflow velocity.
beta      [deg], undisturbed flow angle.
betai     [deg], hydrodynamic Pitch angle.
Gamma     [m^2/s], vortex sheet strength.
CL        [ ], section lift coefficient.
Sigma     [ ], cavitation number.
d_alpha   [deg], inflow variation bucket width.
```

```
Js       = 0.6057
Ct       = 1.2975
Cq       = 0.3916
Cp       = 2.0314
VMIV     = 1.0000
Kt       = 0.1869
Kq       = 0.0282
Eff      = 0.6387
Tau      = 1.0000
Duct Circulation        = 0.0044

Output at the control points for the propeller

r/R             G                       Va              Vt              Ua                Ua(ring)
0.47628  0.051059  1.00000  0.0000  0.26924  0.01431  -0.14958  22.038  28.946  0.30517  0.00800
0.53141  0.051847  1.00000  0.0000  0.28001  0.01477  -0.13431  19.941  26.281  0.29650  0.00800
0.58654  0.053109  1.00000  0.0000  0.29414  0.01529  -0.13222  18.196  24.227  0.29453  0.00800
0.64167  0.054387  1.00000  0.0000  0.30567  0.01590  -0.12634  16.724  22.429  0.29504  0.00800
0.69679  0.055566  1.00000  0.0000  0.31453  0.01659  -0.11970  15.466  20.853  0.29763  0.00800
0.75192  0.056627  1.00000  0.0000  0.32200  0.01738  -0.11353  14.381  19.480  0.30231  0.00800
0.80705  0.057569  1.00000  0.0000  0.32918  0.01826  -0.10854  13.436  18.287  0.30927  0.00800
0.86218  0.058363  1.00000  0.0000  0.33653  0.01921  -0.10505  12.605  17.248  0.31865  0.00800
0.91731  0.058907  1.00000  0.0000  0.34284  0.02017  -0.10321  11.870  16.321  0.33034  0.00800
0.97244  0.058948  1.00000  0.0000  0.33755  0.02113  -0.09101  11.214  15.340  0.34287  0.00800

Output on the duct ring vortices

X/R              G                        UA/VS   UR/VS
-0.45833  0.000411  0.07323  -0.0729
-0.37500  0.000411  0.07997  -0.0874
-0.29167  0.000411  0.08695  -0.1072
-0.20833  0.000411  0.09297  -0.1352
-0.12500  0.000411  0.09334  -0.1781
-0.04167  0.000411  0.06096  -0.2452
0.04167  0.000411  -0.06096  -0.2452
0.12500  0.000411  -0.09334  -0.1781
0.20833  0.000411  -0.09297  -0.1352
0.29167  0.000398  -0.08695  -0.1072
0.37500  0.000257  -0.07997  -0.0874
0.45833  0.000086  -0.07323  -0.0729

Js        [ ], advance coefficient.
Ct        [ ], required thrust coefficient.
Cp        [ ], power coefficient. Cp = Cq*pi/J.
Kt        [ ], thrust coefficient. Kt = Ct*Js^2*pi/8.
Kq        [ ], torque coefficient. Kq = Cq*Js^2*pi/16.
VMIV      [ ], volumetric mean inflow velocity / ship velocity.
Eff       [ ], efficiency = Ct*VMIV/Cp.
Tau       [ ], thrust ratio = propeller thrust / total thrust.

r/R       [ ], radial position of control points / propeller radius.
G         [ ], section circulation / 2*pi*R.
Va        [ ], axial inflow velocity / ship velocity.
Vt        [ ], tangential inflow velocity / ship velocity.
Ua        [ ], induced axial velocity / ship velocity.
Ut        [ ], induced tangential velocity / ship velocity.
beta      [deg], flow angle.
betaI     [deg], hydrodynamic Pitch angle.
c/D       [ ], section chord-length / propeller diameter.
Cd        [ ], section drag coefficient.

X/R       [ ], axial location of duct vortex rings / propeller radius.
G         [ ], duct vortex ring circulation / 2*pi*R.
UA/VS     [ ], axial inflow induced by propeller / ship velocity.
UR/VS     [ ], radial inflow induced by propeller / ship velocity.
```

Appendix J

Naval Architecture Shroud Design Parameters [10].

PROPULSION



ORDINATES FOR NOZZLE PROFILE 19[a]

Y/L	0	1.25	2.50	5.0	7.5	10	15	20	25	30	40	50	60	70	80	90	95	100
X_I/L	18.25	14.66	12.80	10.87	8.00	6.34	3.87	2.17	1.10	0.48	CIRCULAR CYLINDRIC			0.29	0.82	1.45	1.86	2.36
X_u/L	—	20.72	21.07	20.80	STRAIGHT LINE													±6.36

Fig. 70 MARIN's Nozzle No. 19A

Appendix K

Blade Thickness Parameters [10].

Length of the blade sections in percentages of the maximum length of the blade section at 0.6 R	from center lane to trailing edge	30.21	36.17	41.45	45.99	49.87	52.93	55.04	56.33	56.44	Length of blade section at 0.6 R
	from center line to leading edge	36.94	40.42	43.74	47.02	50.13	52.93	55.04	56.33	56.44	$1.969 \frac{1}{Z} \cdot \frac{A_E}{A_O}$
	total length	67.15	76.59	85.19	93.01	100.00	105.86	110.08	112.66	122.88	
Max. blade thickness in percentage of the diam.		4.00	3.52	3.00	2.45	1.90	1.38	0.92	0.61	0.50	Maximum thickness at center of shaft = 0.049 D

Appendix L

Table 9 Thrust Test Results

Current (A)	Power (W)	Speed (RPM)	Thrust (lb)
2.09	355.3	820	10.21
2.59	439.5	940	12.76
2.75	467.5	980	15.31
3.25	551.7	1080	17.86
3.52	598.4	1120	20.41
3.80	645.2	1200	22.97
4.29	729.3	1260	25.52
4.68	794.8	1360	30.62
5.28	897.6	1440	33.17
6.05	1028.5	1560	40.83
7.26	1234.2	1660	48.48
8.25	1402.5	1820	51.03
8.91	1514.7	1940	58.69
10.73	1823.3	2140	66.34
13.20	2244.0	2380	79.10
14.8**5**	2524.5	2580	99.52

Appendix M

Table 10 Revised Cost Estimate

Thruster Component	Price
Propeller Material	$120.00
Propeller Machining	$500.00
Centerpiece Material	$46.00
Centerpiece Machining	$100.00
End Cap Material	$22.00
End Cap Machining	$180.00
Shroud Material/Printing	$450.00
Shaft Material	$8.00
Shaft Machining	$100.00
Strut Material	$24.50
Strut Machining	$25.00
Thrust Bearings	$270.00
DC Brushless Motor (Rotor and Stator)	$700.00
Motor Drive	$795.00
Epoxy and Misc. Parts	$60.00
TOTAL	**$3,400.50**

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