DESIGN OF AN INEXPENSIVE WATERPROOF HOUSING

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***Abstract* - Last year, Lake Superior State University's engineering department started a program in undergraduate research and began the task of developing a remotely operated underwater vehicle (ROV). As the students researched the different technologies available for use they became aware that very little information was available for the design of underwater housings with through-hole connectors and motor shafts. Furthermore, commercially available housings were well beyond their budget. Because of this, they set out to design a low cost housing that could be manufactured either by them or by a local business. The goal was to develop 18" aluminum housings with endcaps for under $200. Multiple housings could then be connected to create an ROV. The housings would be designed for up to 300-foot depths. The endcaps would allow for either through-hole connectors or a motor shaft depending on the application. At this time the students have designed, built and tested the housing design and are well on their way to complete the ROV. It is believed that this information would be useful for a wide variety of audiences including any educational group interested in the development of their own ROV. This paper will discuss the technical aspects of the design process and provide the details for development of a low-cost housing. Complete schematics and a bill of materials will be presented.**

I. INTRODUCTION

A. Project Background

Lake Superior State University (LSSU) is conducting research in the area of control systems, and is concurrently developing underwater electrical and mechanical engineering technologies. The most recent part of this process has been the development of a Remotely Operated Vehicle (ROV) suitable for underwater use at depths up to 300-feet. This ROV will be used as a platform for future engineering research and as an educational tool to promote the University. The four major design considerations for the ROV were the operating environment (The ROV must be waterproof and chemically compatible), budget, maneuverability, and the ability to accommodate future research projects.

B. Current Status

The ROV was successfully completed in the spring of 2003 by a team of four students as part of their senior level electrical and mechanical engineering course work. Refer to Fig. 1 for an image of LSSU's ROV. Three junior level students also contributed significant effort in the completion of the ROV.

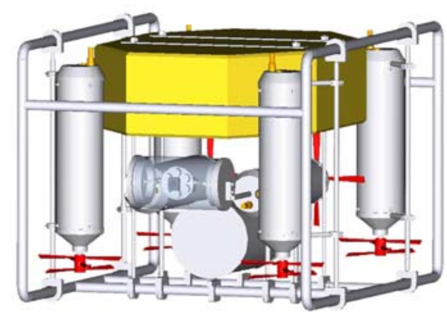


Fig. 1: The ROV developed at LSSU

C. What is an ROV

An ROV is an unmanned mobile machine controlled by a human from a remote location. ROVs are usually designed to operate in harsh environments while the operator remains clear of harms way. LSSU's ROV is designed for underwater use. An underwater ROV will typically collect data such as temperature, depth, heading, pitch, roll, motor speed, and water leakage using sensors to indicate the vehicles operating parameters and surroundings. They also have a vision system to relay the ROV's field of view. All underwater ROVs are comprised of several similar components, the most important being the waterproof housings.

The remainder of this document will describe basic HOUSING TYPES. It will focus on the design of the motor housing, explain the DESIGN CONSTRAINTS and list the COMPONENTS associated with LSSU's ROV housings.

II. HOUSING TYPES

Some underwater ROVs are designed to operate at depths over 23,000-feet, such as Oceaneering's Magellan 725 [1]. The pressure associated with these depths is very high and can cause materials to crush or buckle. Most underwater ROVs operated at much less depth, but in every instance housings are necessary to protect the critical electronics associated with the ROV. Therefore, the housings must not only be waterproof but also capable of handling the external forces from the water. All components, especially the seals and housing material must be designed to withstand the pressure experienced by the ROV.

Most ROVs have similar housing types. These housing types are generally referred to as electronics housings, camera housings and motor housings. Housings are generally comprised of a tubular hull and endcaps. Depending on the housing type there are several points where water leakage is a concern. The following sections will discuss the housings used by LSSU's ROV.

A. General Electronics Housing

The general electronics housing is used to protect the electrical components. In the case of the ROV built at LSSU, the main electronics housing contains an orientation sensor, power distribution boards, temperature sensor, an external pressure sensor to calculate depth, microcontrollers (small computer processors), and the supporting electronics for the microcontrollers. The electronics housing, shown in Fig. 2, is comprised of a tubular aluminum hull, a connector endcap with a pressure fitting, a sensor endcap, and endcap o-rings. The process used to design these components will be discussed in greater detail later in this document.

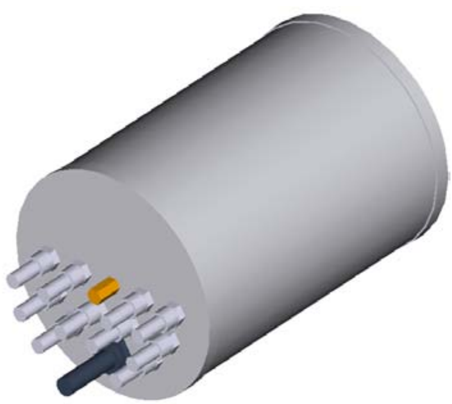


Fig. 2: General Electronics Housing

B. Camera Housing

Since ROV's generally operate out of human vision and at depths where light is limited, a vision system inside a camera housing must be incorporated into the vehicle design. The camera housing protects the camera, lighting, and support electronics from the outside environment. In the LSSU ROV's case, the housing is constructed much like the general electronics housing except that the tubular hull is constructed out of a clear acrylic instead of aluminum and the endcap opposite the connector endcap does not have sensors mounted on it. Similar to the general electronics housing, the camera housing has a connector endcap with a pressure fitting and o-rings (refer to Fig. 3).

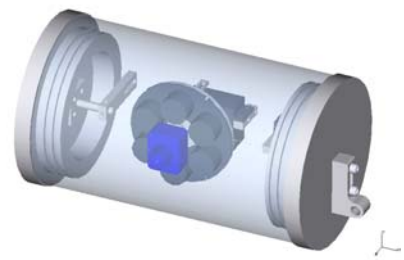


Fig. 3: Camera Housing

C. Motor Housing

The most demanding housing to design was the motor housing. Although this housing is similar to both the camera and electronics housings it also incorporates a greater design task of sealing a protruding motor shaft. The motor housing, shown in Fig. 4, is comprised of a tubular aluminum hull, a connector endcap with a pressure fitting, a motor endcap, and o-rings. The motor housing must also provide a mounting location for a motor and the supporting electronics and sensors. The remainder of this document will focus on the design of the motor housing because of its similarities to the other housings. Refer to the exploded drawing at the end of this document.

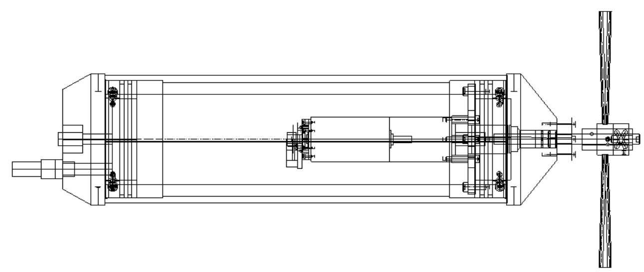


Fig. 4: Assembled Motor Housing

III. DESIGN CONSTRAINTS

The design constraints and challenges that were considered when designing the ROV's motor housing were:

A. Waterproof / Shock Absorption

All housings were required to provide a watertight seal and the motor housing was required to protect the motor from radial loading on the shaft (most motors cannot withstand forces along the shaft that push or pull on the motor). Watertight seals (o-rings) must operate at all depths from the surface down to 300ft. The shaft seals must be able to withstand the temperature changes that occurred from friction and the possibly cold temperature of the water that the vehicle is operating in.

Standard and thrust bearings must also be incorporated in the design to align the propeller shaft, absorb the radial load (stress associated with rotation) and the axial load (stress from the pushing and pulling of the shaft).

B. Chemical Compatibility

The ROV must be designed for operation in a chlorinated pool and for fresh or salt-water environments. The housings, the seals, and other materials exposed to the water must be designed to be non-corrosive and durable under these conditions.

C. *Pressure Capabilities*

As previously mentioned, the ROV must operated at depths down to 300 feet. At this depth the ROV will experience approximately 130psi. Assuming the density of water is 62 lbs/ft^3 and disregarding the changes associated with temperature, the relationship between pressure and depth can be approximated as shown in (1.4).

$$\rho = 62\frac{lb}{ft^3} \quad \textit{Density of water} \tag{1.1}$$

$$p_0 = 14.7\,psi \quad \textit{Atmospheric pressure} \tag{1.2}$$

$$g = 32.174\frac{ft}{\sec^2} \quad \textit{Gravity} \tag{1.3}$$

The atmospheric pressure can been discarded if a vacuum is applied to the inside of the housing so that seals seat. Chart 1 represents the correlation between pressure and depth.

$$pressure_{depth} = p_0 + \rho \cdot g \cdot depth - p_0 \tag{1.4}$$

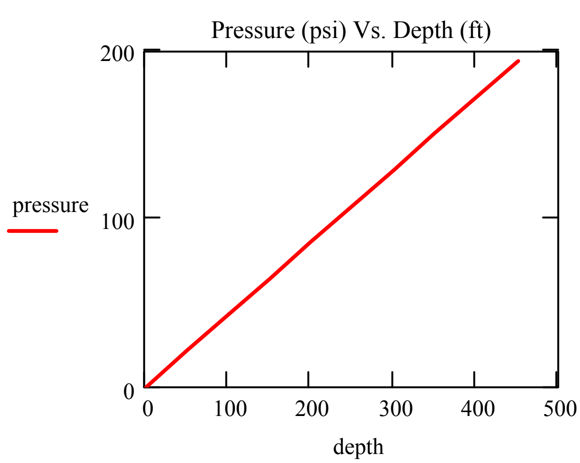


Chart 1: Pressure Vs. Depth

Chart 1 shows that for every 10 feet below the water, the pressure will increase by approximately 4.3psi. The seals must be able to withstand this pressure without leaking. Yet, the shaft seal must not create excessive friction or power losses will result when turning the motor shaft. Finally, the aluminum wall of the hull must be able to withstand the pressure without deforming.

D. Cost

The majority of this ROV project is funded through Lake Superior State University. Therefore, financing is a concern because there is no industry backing. A list of the components, the vendors and the cost associated with each part is included later in this document.

E. Size

When designing the motor housing the overall size was a concern because the ROV must be maneuverable and the larger the vehicle, the less agile it is. At the same time, the housing is design to hold a motor and supporting electronics and must provide adequate room to do so. The overall goal was to make the vehicle as small as possible but flexible enough for future research.

F. *Expandability*

The intention of this ROV project was to design and build a platform to be used for future electrical and mechanical research projects at LSSU. To help meet this goal the motor housing was designed to be larger than required. The additional room will allow for a variety of motor/gearbox combinations to be researched. It will also allow for additional electrical equipment to be mounted inside. The housing was also designed to accommodate several mounting configurations. This will allow the housings to be repositioned if necessary during future modifications.

IV. COMPONENTS

Several components went into the design of the waterproof motor housing. These components will be discussed in greater detail throughout the remainder of this document. A dimensioned drawing is included at the end of this paper.

A. Tubular Enclosure

The tubular enclosure is the largest component of the motor housing. It was designed to resist pressures found at 300-foot depths, accommodate a variety of electric motors, and provide a watertight seal by interfacing with two endcaps. Acquisition and machining costs were also kept to a minimum. Aluminum tubing with an inner diameter of 4-inches and a length of 14-inches were basic measurements decided upon, since the largest suitable electric motor had a diameter of 3.25 inches. The pressure housing has a maximum working pressure of 130psi, but a generous safety margin called for a 200psi design pressure. Equation (2.1) calculates the required ratio of wall thickness to outer diameter to avoid metal deformation as a function of the material's yield stress and pressure [2]. Equation (2.2) calculates the required ratio of wall thickness to outer diameter to avoid buckling as a function of the material's modulus of elasticity, Poisson's ratio, and pressure [2]. 6061 aluminum has a yield stress of 8ksi, a modulus of elasticity of 10,000ksi, and Poisson's ratio is 0.33.

$$T \ to \ D \ Ratio = \frac{1}{2}\left(1 - \sqrt{1 - \frac{2 \cdot pressure}{yieldstress}}\right) \quad (2.1)$$

$$T \ to \ D \ Ratio = \left[pressure \cdot \left(\frac{1 - v^2}{2 \cdot ModOfElasticity}\right)\right]^{\frac{1}{3}} \quad (2.2)$$

The resulting thickness to outer diameter must be at least 0.021 to prevent buckling at 200psi. Tubing with a wall thickness of 0.25 and an outer diameter of 4.50 inches (the thickness to diameter ratio is 0.056) was chosen. The wall thickness is much greater than necessary, but the increased wall thickness allows 2 inches of the inner wall at both ends of the tubular housing to be precision machined to a diameter of 4.130 inches. The machined surface allows a watertight seal to be achieved when the endcaps are inserted. This watertight seal design is discussed in the O-Rings/Seals section.

B. Connector Endcap

Two endcaps form the ends of the pressure housing. Both endcaps are constructed of 6061 aluminum. Parker Machine & Engineering, Inc. machined the endcap profiles while the remaining operations were completed at Lake Superior State University. The seal design between the endcaps and the tubular housing is discussed in the O-Rings/Seals section. One endcap allows a rotating shaft to pass through, while the other allows wires to pass through and also provides a means of withdrawing the air from the housing. The endcaps are called the connector endcap (Fig. 5) and the motor shaft endcap (Fig. 6) respectively.

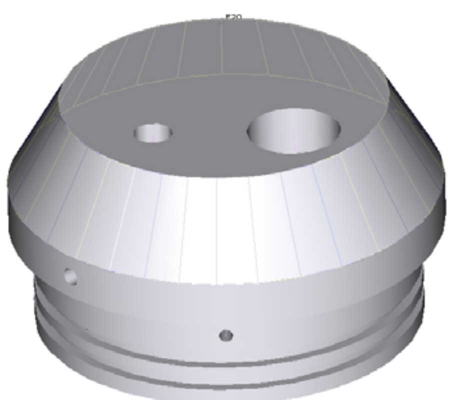


Fig. 5: Connector Endcap

The connector endcap has two through holes that are threaded for securing a pressure fitting and a waterproof electrical connector. The pressure fitting allows a near vacuum to be established within the housing with a vacuum pump. The 5 wire electrical connector allows power and communication signals to enter the tube. A slight taper is added for hydrodynamic effect.

C. Connector

The electrical connector is a 5-pin connector purchased from Subsea Video Systems Inc. The connector is commercially rated for the equivalent pressures of 300 feet and capable of conducting 3.5 amps.

D. Pressure Valve

A pressure valve was obtained through the LSSU maintenance department. The valve is used to apply a vacuum to the tube before placing the vehicle in the water. The vacuum helps to seat the seals. The valve is a standard air conditioning fitting with a tapered pipe thread.

E. Motor Shaft Endcap

The motor shaft endcap is 6061 aluminum that was partially completed by Parker Machine & Engineering, Inc. The remaining machining operations were completed at Lake Superior State University. The motor shaft endcap has a 0.624-inch hole bored along its axis. This hole is where the shaft passes through, and is made watertight with two shaft seals from Parker Hannifin. The shaft is supported by two ball bearings, one of which is pressed into place immediately behind the second seal. The second bearing is pressed into a 0.874-inch diameter counterbore at the inside end of the hole. The motor shaft endcap

Fig. 6: Motor Shaft Endcap

provides mounting points for the motor mount and the shaft seal retainer. To remove the endcap from the tubular enclosure, ¼” – 20 stainless steel screws were inserted into each endcap and then gently pulled apart.

F. O-rings/Seals

Two Viton o-rings are set into grooves in each endcap. The grooves are sized according to instructions given by the o-ring manufacturer, Marco Rubber. When an endcap is inserted into the tubular housing the o-rings are compressed by 0.015 inch. This compression renders a watertight seal capable of sustaining 1200psi. The motor shaft endcap has a hole with a diameter of 0.625 inches bored through its center. This hole allows a polished stainless steel shaft to pass through. The rotating shaft is sealed to 1250psi with two carboxilate-nitrile deep polypak u-cup shaft seals from Parker Hannifin. The shaft is supported with two ball bearings, one of which is pressed into the hole.

G. Seal Retainer

To ensure that the shaft seals do not walk off the shaft, a retaining disk is used. The disk was manufactured at LSSU and is secured to the shaft endcap. Refer to Fig. 7 for a visual representation.

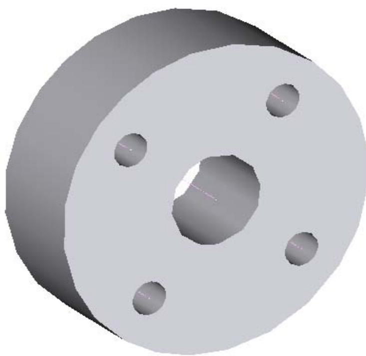


Fig. 7: Seal Retainer

H. Bearings

Champion Bearings Inc designed the bearings selected for this application. There are two bearings used to absorb the loading of the propeller and keep the propeller shaft aligned. Both bearings are rated as ABEC3 and have ceramic ball bearings, stainless steel raceways, and Teflon impregnated seals. The ceramic balls create less noise and produce less heat. This increases the life of the bearing by 3-5 times that of a steel ball. The stainless steel housing and raceways were chosen because of the environment. The bearing may come in contact with water and rust would form if it were made from soft steel. The Teflon seals are designed to withstand pressures above 500psi. These seals have been proven at LSSU at 200psi and are the last defense against water intrusion in the event that the shaft seals fail.

The inner bearing is designed to absorb a maximum of 750-lbf of axial load created by the propeller. This is done to protect the motor from the continuous shock and stresses. The bearing is flanged with an inner diameter (ID) of 3/8-inches, and an outer diameter (OD) of 7/8-inches. The bearing is gently pressed in and the flange rests flush against the inner edge of the motor shaft endcap.

The outer bearing is designed to fit in the 5/8-inch opening for the propeller shaft. This relatively small outer diameter was used because the shaft seals available in the self lubricating carboxilate nitrile was limited to an outer diameter of 5/8-inch. The bearing is also gently pressed into the motor shaft endcap with a thrust bushing between it and the inner bearing. The main purpose of this bearing is to absorb a maximum of 150-lbf of radial load and alignment of the propeller shaft.

I. Propeller Shaft

The propeller shaft was purchased in 6-inch lengths from Rino Mechanical. It is type 304 stainless steel that has been precision ground to 0.3748” in diameter. The precision shafting is important because it provides a smooth sealing surface to minimize seal wear and is precisely the right size for our bearings. A removable thrust collar is held in place with a setscrew that lands in a dimple machined into the shaft.

J. Motor Shaft Coupler

The motor shaft coupler allows the drive shaft of the motor to securely transmit torque to the propeller shaft. The coupler is an Oldham style, and affords a misalignment of 0.005 inches. The coupler disks determine the rated torque that can be applied to the coupler, which is 672 in-oz.

K. Motor Mounting Plate

Various mechanical fixtures were manufactured at LSSU to secure the motor and associated electronics within the motor housing. The hardware provides accurate alignment of the motor with the motor shaft endcap and motor shaft. Refer to Fig. 8.

Fig. 8: Motor Mounting Plate

L. Motor

The motor is a 48-Volt ultra-low inductance brushed gear motor made by Maxon. This motor produces 352 in-oz of torque while spinning at 505 RPM and has a maximum current draw of 3.125 amperes. The gear motor is dual shafted, and the reduced end is attached to the through hull shaft via a flexible shaft coupler, while the other end is attached to an incremental encoder from US Digital. The pulses from the encoder are used to determine motor speed for feedback control functions. The motor draws approximately 1.7 amps at full load with the current propeller configuration.

M. Mounting Hardware

Stainless steel socket head cap screws were used to attach the endcap to the tubular enclosure. The cap screws were also use in conjunction with aluminum standoffs to mount the motor to the motor mounting plate. The plate was then mounted to the motor shaft endcap. To remove the endcap from the tubular enclosure, stainless steel screws were used.

V. THEORETICAL EXPECTATIONS

The foremost expectation of the waterproof housing is to be able to maintain operation at depths up to 300-feet. The ability to maintain operation includes preventing water from entering the housing and maintaining structural integrity. Lastly, the total cost of the waterproof housing must be under 200 dollars.

VI. TEST RESULTS

To confirm the theoretical expectations, each housing was put through three separate tests. The first test was to place a vacuum on the internals of the housing. The second was to pressure test each housing in a pressure-testing vessel. The third test was to dynamically test each motor on a test stand in water to assure that no leaks were present.

A. *Vacuum Testing*

Vacuum testing is performed in order to ensure that the seals seat and that the housing does not have any slow leaks, specifically at low pressures. This test was performed using an electric vacuum pump with an air-conditioning (a/c) valve/gauge system. A near vacuum was applied to each housing and read visually from the a/c gauge. The housing was monitored for three hours in this state. If the pressure was increased after the three hours expired then the housing was to be inspected to find the area of the leak. Fortunately the design was a success and each housing pasted the vacuum test. Once the housing passed the vacuum test it was tested in a pressure vessel.

B. *Pressure Testing*

Each housing was place in a pressure vessel built and designed at Lake Superior State University. The housing was submerged in the vessel, and the pressure was increased to 200psi. The test was conducted at 200psi to ensure that the ROV was stable when operating pressures associated with 300-feet. Once the pressure reached 200psi in the pressure vessel, it was held for three hours. The pressure gauge on the vessel was monitored to ensure that the internal pressure stayed above 180psi. Once the three hours expired, the housing was removed from the pressure vessel and inspected for leaks. If water was present then the leak was to be found and remedied. In the case of the ROV designed at LSSU, the housings were all waterproof in the pressure vessel. Once this test was completed and each housing had passed, they were dynamically tested on the motor test stand.

C. *Dynamic Motor Testing*

At this point in the testing process all of the electronics were added so that the motor housing propeller shaft would rotate and the seals could be tested under dynamic conditions. The motor test stand consisted of a stationary device that would keep the motor housing submerged and free from interfering obstacles. Dynamic leak testing will be conducted in order to demonstrate the ROV's ability to function in the water. The test stand allows the user to test for leaks while the motor operates and to also measure characteristics of the housing, such as thrust, current draw, and efficiency.

VII. BUDGET

Each component was selected for functionality and with great regard to cost effectiveness. All sealing surfaces were designed around standard o-ring and shaft seal sizes. This kept seal costs to a minimum because custom seals were not required. Machine work was completed in house if possible and in some cases Parker Machine & Engineering, Inc. of Woodhaven MI. donated their time and resources to machine parts. The bearings were built to meet the specific need of the ROV, but were still relatively low cost items. A goal of $200 per housing was established and achieved by using students to build many of the components at LSSU.

Table 1 provides a list of all components purchased to produce the motor housing. The total cost of each motor housing was about 188 dollars.

Table 1: Itemized Motor Housing Budget

Part Number	Item Description	Vendor	Qty	Total Cost
12500375-250BN4257	Radial Seals Carboxilate Nitrile	Zatkoff Seal And Packing	2	27.58
-240	O-Rings	Marco Rubber	4	3.36
SFR6LLCB	ABEC3 Ceramic Bearings	Champion Bearing Inc	1	18.00
SR1038LL CB	ABEC3 Ceramic Bearings	Champion Bearing Inc	1	17.50
GS3750-60	Shafts	Rino Mechanical	1	3.45
NA	Schrader Valve	Donated	1	---
0CT16-6-A	3/8 Coupler End	Ruland	1	12.32
IOCT25-12-A	12mm Coupler End	Ruland	1	12.32
O016/25-AT	Coupler Disk	Ruland	1	2.13
NA	6061-T6 Aluminum Round	Alro	1	15.86
NA	6061-T6 Tube	Alro	1	18.83
NA	6061-T6 Sheet	Donated	1	---
NA	Socket Head Cap Screws	McMaster Carr	1	2.50
SCN5C	Cable Connector	SubSea Video Sys	1	26.95
SCN5BHD	BulkHead Conn	SubSea Video Sys	1	26.95
Total				**187.75**

VIII. CONCLUSION

Lake Superior State University's engineering department initiated an undergraduate research program. As part of this research program a team of students were given the task of developing a remotely operated vehicle (ROV). During the investigation, it was realized that all ROVs would require a waterproof housing. With commercially available housing being well beyond the budget of the research program, the students began to develop an inexpensive and easy to manufacture housing. The goal was to develop a waterproof housing capable of withstanding 130psi (equivalent pressure associated with a depth of 300-feet) and be manufactured for under $200.

The endcaps must allow for both through-hole connectors and a pressure valve or a motor shaft, depending on the application. A waterproof housing, costing $188.00 was developed by the students at LSSU. This waterproof housing was designed to operate at 300-feet. The design was then pressure tested to 200psi (approximately 465 feet) to ensure a safety margin exists when operating at maximum depth. However, the majority of the components comprising the waterproof housing will greatly exceed the design constraints.

Acknowledgments

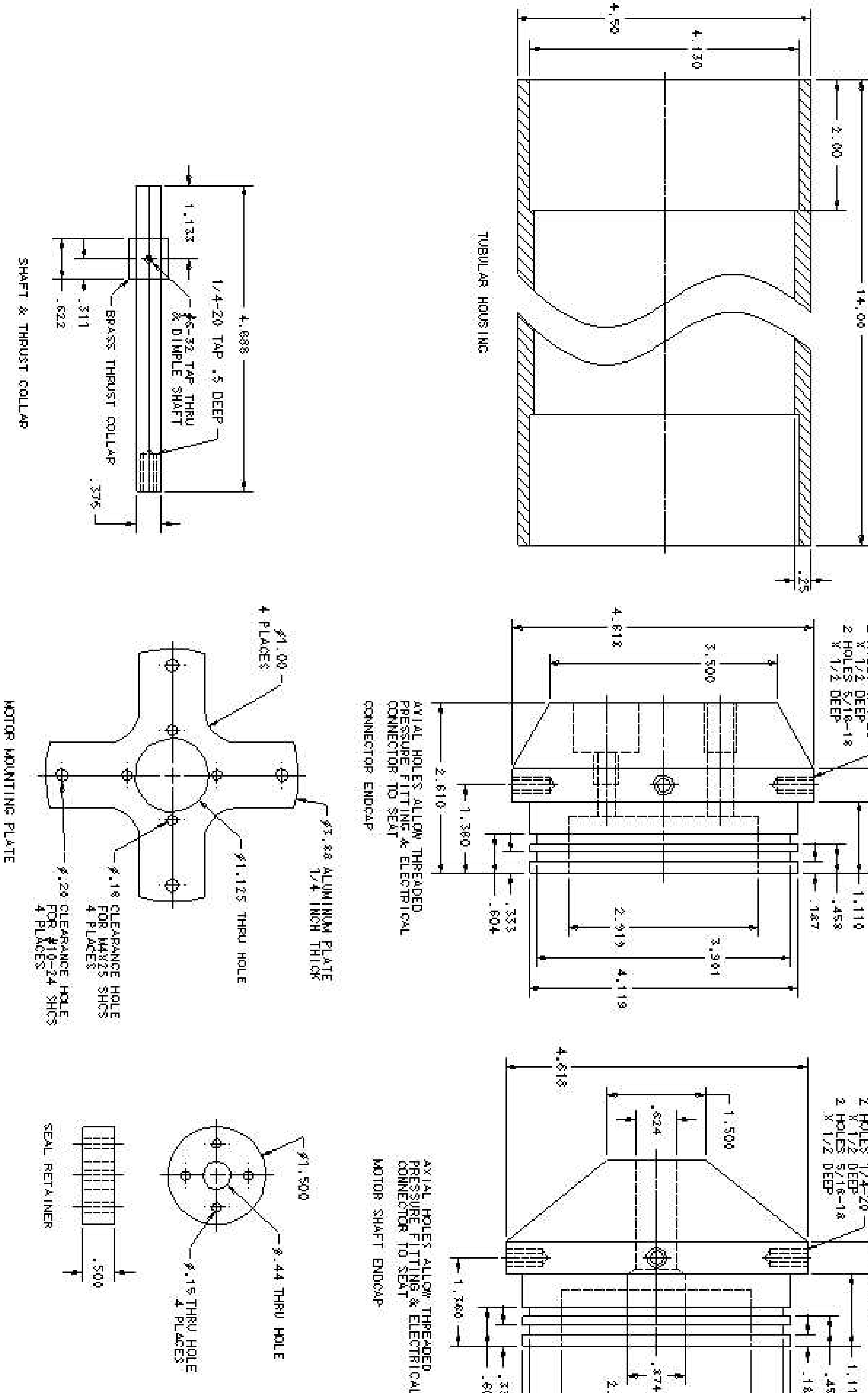
Team RADAR would like to thank the Seacon & Brantner donated the main bulkhead connector used to mate the ROV and the tether. Maxon Motor was very helpful and allowed for an educational discount for the six motors used to propel the vehicle. Microchip Technology provided sample PIC18F452 microcontrollers for the motor controllers. Parker Machine & Engineering, Inc. contributed to the project by machining the tubes and endcaps. The team would like to acknowledge the vast amount of assistance the members of EG260 (Under Graduate Research Methods) have put into the ROV project. Lastly, Team RADAR would like to thank LSSU for their funding and support for the duration of this project (especially Professor Morrie Walworth).

Reference

[1] ROV - Magellan 725 ROV - Oceaneering Int. Inc, http://www.oceaneering.com/adtech/rov/ adtech_725.htm.
[2] Roger Cortesi SM., "Simple Pressure Failure Modes," http://pergatory.mit.edu/rcortesi/portf/uec/downloads/Simple%20Pressure%20Vessel%20Failure%20Modes.mcd}.

Exploded View of Motor Housing

1. Electrical Connector
2. Pressure Fitting
3. Connector Endcap
4. Mounting Hardware
5. Tubular Enclosure
6. Motor
7. Mounting Hardware
8. Motor Mounting Plate
9. Mounting Hardware
10. Shaft Coupler
11. Mounting Hardware
12. Motor Shaft Endcap
13. Bearings
14. Seal Retainer
15. Shaft Seals
16. Propeller
17. Motor Shaft


14.00
2.00
.25
4.130
4.50
TUBULAR HOUSING
2 HOLES 1/4-20
X 1/2 DEEP
2 HOLES 5/16-18
X 1/2 DEEP
.500
1.110
.458
.187
3.500
3.901
2.919
4.119
4.618
.333
.604
1.360
2.610
AXIAL HOLES ALLOW THREADED
PRESSURE FITTING & ELECTRICAL
CONNECTOR TO SEAT
CONNECTOR ENDCAP
1.500
.624
.874
MOTOR SHAFT ENDCAP
4.688
1/4-20 TAP .5 DEEP
1.133
#6-32 TAP THRU
& DIMPLE SHAFT
BRASS THRUST COLLAR
.311
.622
.376
SHAFT & THRUST COLLAR
ø3.88 ALUMINUM PLATE
1/4 INCH THICK
ø1.00
4 PLACES
ø1.125 THRU HOLE
ø.16 CLEARANCE HOLE
FOR M4X25 SHCS
4 PLACES
ø.20 CLEARANCE HOLE
FOR #10-24 SHCS
4 PLACES
MOTOR MOUNTING PLATE
ø1.500
ø.44 THRU HOLE
ø.15 THRU HOLE
4 PLACES
.500
SEAL RETAINER