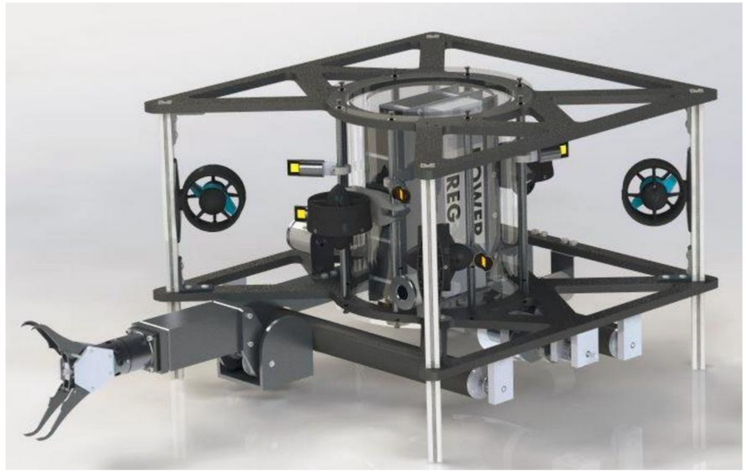
Wentworth Institute of Technology

BOSTON, MA



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Abstract

In a world that utilizes underwater technology and systems, there is a demand for maintenance and repair to preserve productivity. Currently, Commercial divers risk their lives by working in dangerous conditions to complete what would otherwise be a mundane task. Our driving ideal is to keep them safe. We are designing a UROV (Underwater Remote Operated Vehicle) that can complete simple tasks to keep divers out of danger. The concepts of these designs will be tested at the MATE (Marine Advanced Technology Education) competition. From the design specifications for the competition as well as our own requirements, the UROV will be held to the following standard of completion. For the competition the UROV must be able to complete three demonstrations; Science under the ice, Subsea pipeline inspection and repair, and offshore oilfield production and maintenance. Additionally, the goal of operating at a depth of 30 meters was set such that our ROV would be capable of easily reaching the underside of ships for maintenance and repair and performing real world tasks at greater depth than our previous year's ROV.

Contents

Design Rationale

Housing

The housing serves as the main starting point for the ROV's mechanical design since its purpose directly affects the performance of the vehicle. The housing must be able to keep all electronics dry while allowing easy access to electronics if necessary. Since the housing is sealed, the mass of water that it displaces defines the absolute minimum amount of ballast necessary for neutral buoyancy without other structural components factored in. In our design, a 12 inch long, 10 inch diameter acrylic tube was used and displaced nearly 15 kg of water. After performing research and FEA simulation, it was determined that a cylindrically shaped housing is the best shape for our application. Although it is not the most space efficient shape for storage, a cylinder is more capable of handling pressure when compared to a box of similar wall thickness and volume. When comparing shape characteristics under pressure, the yield strength of the material is compared to the maximum Von Mises stress point on that given shape. It can be seen in Figure 1 that the maximum Von Mises stress point does not exceed the yield strength of that material, so it is capable of reaching 30 meters underwater. The box shape in Figure 2 has a stress point greater than the yield strength which means it would fail under the pressure at 30 meters

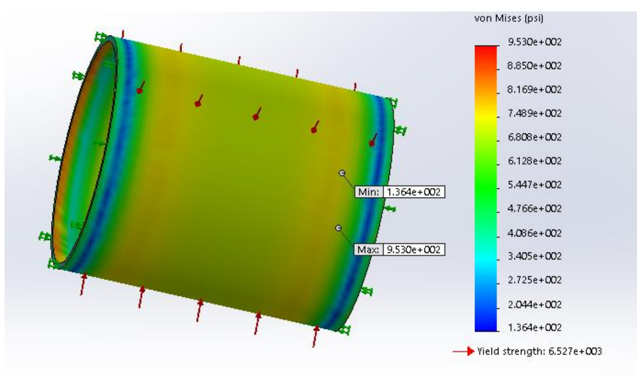


Figure 1: Cylindrical tube of Acrylic under stress at 33 meters under water

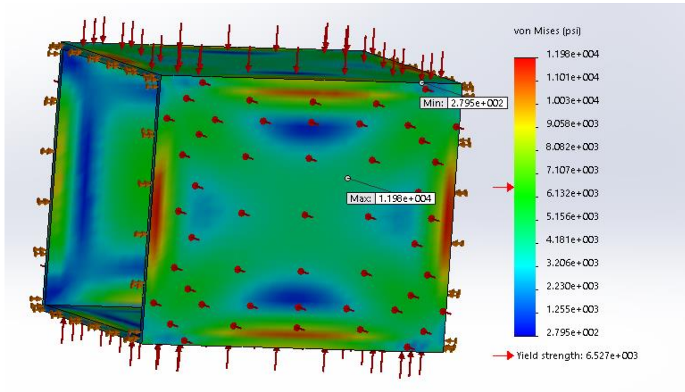


Figure 2: Box of Acrylic under stress at 100 feet under water

1/4 inch acrylic was chosen for the material for the housing due to its optical clarity and physical properties. They clarity grants us the capabilities of mounting additional cameras within the housing without the need to design any further waterproofing system. Acrylic also has an acceptable yield strength in terms of our design goals and operating conditions. Accompanying the acrylic tube on either end are two half inch end caps made of 6061 corrosion resistant aluminum. The design of each vary from one another since one end cap was determined to be permanent where the other is meant to be removable. As seen in Figure 3, The permanent end cap has two boss rings that hold the wall of the acrylic tube tightly. Any void between the acrylic and aluminum is filled with 5200 marine sealant to ensure a perfect watertight seal.

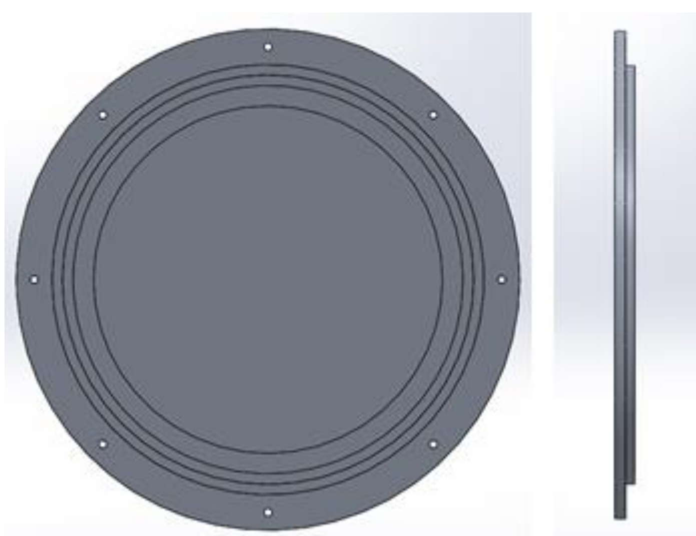


Figure 3: Permanent end cap design. Front view (left), side view (right)

The removable end cap located on the top side of the acrylic tube has more of an intricate design. There are grooves cut to welcome both a face seal and radial seal which will come in contact with the acrylic tube. The face seal will be pressed against the rim of the acrylic tube and the radial seal will be squeezed in between the inside of the tube and the outside of the extruded lip of the plate. Buna-N rubber is the material of choice for sealing the housing. Its elastic properties are well suited for creating a tight seal as well as maintaining its properties in cold temperatures. The removable end cap will also hold onto the electronics plates that will be suspended in the housing. In Figure 4, the two rims running horizontally across the face is the mating surface for the electronics plates. This allows for easy removal of the electronics as well as a source for heat dissipation. Since some components will be producing heat, having the aluminum end cap in contact with the water will allow for efficient heat transfer to take place.

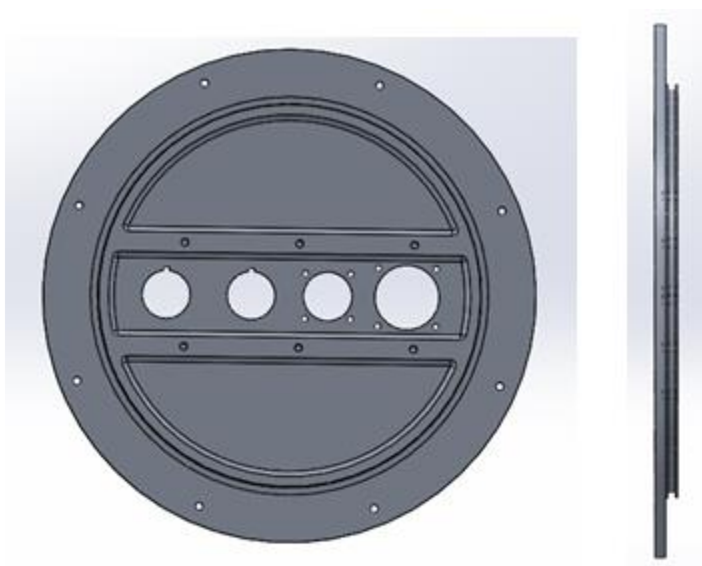


Figure 4: Removable end cap design. Front view (left), side view (right)

Figure 5: Side View of Housing

Both aluminum plates are being squeezed onto the acrylic tube through the use of tapped aluminum bars as shown in Figure 5. The use of these bars eliminates any need for unnecessary through holes in the housing, reducing possible failure points. They also provide an added form of protection for the acrylic tubing from any potentially large objects encountered while under water. The aluminum bars also allow secure attachment to the chassis.

The removable end cap will be responsible for interfacing the tether to the electronics plates through the watertight connectors. These four connectors will be running parallel to one another which conveniently fit in between the electronics plates to consolidate wire management.

Electronics

Modularity was the major design motivation with regards to the electronics this year. An important goal was to be able to swap out instrumentation, sensors, and other modules with minimum effort. We utilized a modified Arduino Mega for the onboard logic hub as seen in Figure 6, with a serial to Ethernet bridge to allow us to take advantage of the flexibility and simplicity of TCP communications protocols. The Arduino interfaces with a custom logic distribution board that provides three DB9 connectors, one DB25 connector, and eight 3-pin headers. Modules can be plugged into any of the D-sub connectors, where they have access to digital and analog IO, an I2C bus, and power. Additional modules can be daisy-chained, allowing for more than four concurrent instrumentation sets. IO pins and module mappings are reassigned dynamically when the robot initially connects to a control

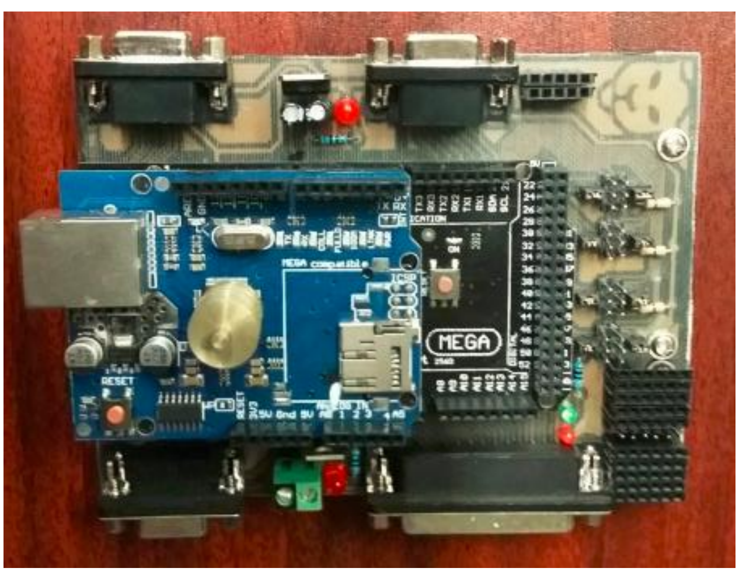


Figure 6: Logic Hub

station, and can be changed on the fly - there is no static configuration within the microcontroller.

Currently, the implemented modules include a sensor array, stepper drivers, an 8-way dual channel camera switcher, and a coprocessor for the encoder measurement mechanism. Our primary navigational sensor is the HMC5843, a high-end magnetometer, gyro and accelerometer combination that accurately and quickly supplies absolute positioning, invaluable for maintaining software stabilization. A pressure sensor is implemented as a depth sensor, allowing us to maintain a specific depth.

We utilize six, 3-phase brushless BlueRobotics T100 thrusters in a vector configuration for drive, and three stepper motors to actuate our manipulator arm. 30A ESCs drive our thrusters, and a custom stepper driver board based on the DRV8825 gives us precise control of our stepper motors.

Power regulation is performed by a modified Telco server power supply. This device can accept a variable input voltage of 32-72 volts and supply up to 110 amps burst or 80 amps continuously at 12 volts. Custom regulators onboard also provide 5v and 3.3v rails for logic and sensors, and an additional regulator provides 24v for our stepper driver.

Chassis

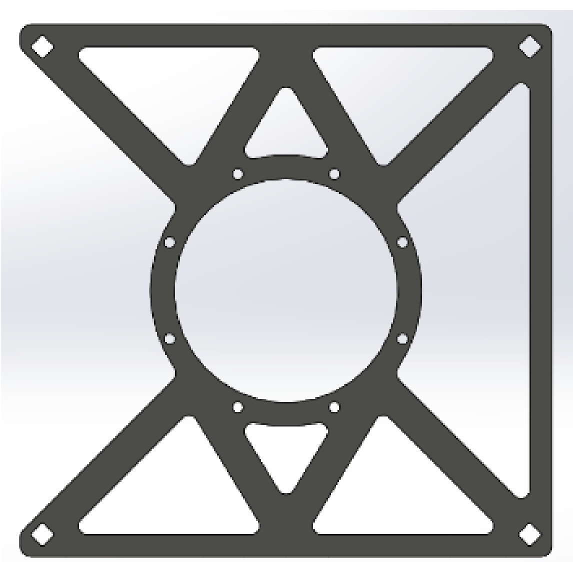


Figure 7: HDPE frame profile

The design of the chassis is very simple, rigid, and can be easily modified. The materials used are marine grade high density polyethylene (HDPE) and 80x20 extruded aluminum. HDPE is a strong and rigid plastic but can be easily machined which allowed us to customize the shape of the frame as shown in Figure 7. HDPE also has great properties for underwater applications such as very low glass transition temperature of -80 degrees C and water absorption resistance. This means that it won't become brittle in near freezing temperatures and that its dimensions will not change greatly due to swelling from water absorption. The extruded aluminum makes it very easy to attach and move components around once implemented on the ROV. This is what adds to the modularity of the design. The ROV's capabilities are not limited to its current design since tools and instrumentation can be moved and changed at various points along the frame. Currently, the extruded aluminum is supporting the horizontal thrusters in a vector drive configuration. This is a common configuration for ROVs in industry since it provides a wide range of maneuverability. Vector drive allows the ROV to rotate and translate along the horizontal plane in any direction. This is ideal for maintaining heading in a current, or keeping a visual on a point of interest while repositioning the ROV.

Manipulator

Claw and Arm

Figure 8: Finished Manipulator

This system allows independent claw actuation and continuous wrist rotation through a single sealed output shaft driven by a NEMA 17 electric dual motion actuator (DMA). This actuator is composed of a linear and rotary stepper motor attached to a single shaft. Stepper motors were selected originally for their synchronicity and because they are relatively easy to control. They allow easy position control without encoders due to the nature of their construction. Also, they exhibit high torque at low RPM, and have a greater power/cost ratio than other common motors such as servos.

The claw actuation performs the necessary gripping of objects and samples in the underwater environment. This motion is performed by the linear stepper motor inside the actuator. Through static force analysis it was calculated that the linear force produced by the

DMA translates to approximately 12 to 30 pounds of closing force at the outer and inner jaws respectively. At maximum extension as shown in Figure 9, the jaws of the manipulator open to about 7 inches, giving it a similar grip size range to that of a large human hand. This was done to mimic the grip capability of the commercial divers that this ROV is designed to aid or replace. This function will be utilized throughout the competition for tasks such as the collection of a sea urchin off of the sea floor and deploying a passive acoustic sensor. It will also be used while inserting a hot stab to simulate injecting corrosion prohibiter into the wellhead. To perform more specific gripping or cutting tasks, the jaws may be easily swapped out with another custom set, through the simple removal of 5 screws.

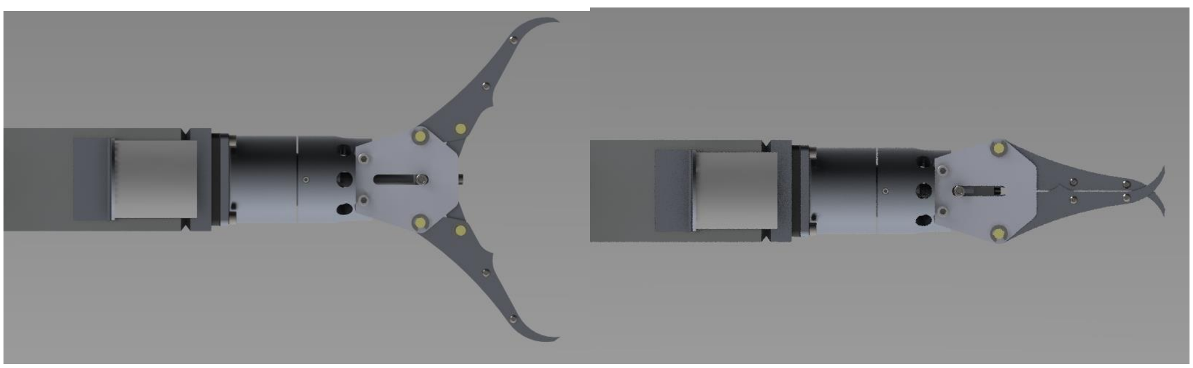


Figure 9: Claw in Full Open and Closed Positions

Continuous wrist rotation is performed through a double-stack rotary stepper motor within the DMA. This function of the manipulator became a desired feature because it would provide a significant advantage for the ROV while rotating pipeline valves. Without a dual motion actuator, the rotation range would be limited by wires as in other common systems utilizing a combination of single motors. This would require rotation tracking in order to make sure the wires were not over extended during rotation. Additionally, those wires may become hung up on underwater structures during use, causing damage or loss of ROV systems. This design provides versatile functionality underwater up to the design constraints dictated by the MATE ROV competition. The competition requires up to 3.25 rotations of a brass gate valve in order to fully open or close certain sections of a pipeline. Empirical test results returned a maximum starting torque of 20 oz-in for the valve as specified in the competition mission props part list. This was a critical design requirement that is answered by the 50 oz-in of torque supplied by the rotary stepper motor of the DMA.

As with all underwater robotics systems, waterproofing is a major design requirement that is at the root of every design. This manipulator is no exception. Once it was verified that the actuator met the design specifications for power and system compatibility, seal design and selection immediately began. The necessary seals on the final design include a Polyurethane shaft seal and two Buna-N face seals. Elastic sealing pressure is applied to the 316 stainless steel output shaft in order to maintain a watertight seal at pressures up to 3 bar as specified by the manufacturer [Harwal Seals]. Polyurethane was chosen because of its resistance to extrusion under high pressure, low temperature tolerance, and the low level of friction on the shaft seal when lubricated. The cross section of the shaft seal is shown in Figure 10. This is pressed into the DMA casing shown in cross section of Figure 11 such that the water will be on the left face of the seal and the inside of the case will be to the right. Face seals are used on either side of the DMA flange. These seals consist of 1/16" Buna-N sheet rubber which compresses and seals the actuator case when the faces are screwed together. Buna-N rubber, like Polyurethane, is also capable of maintaining a seal in the near 0 degree C water temperatures of the Arctic.

Figure 10: Cross section of shaft seal

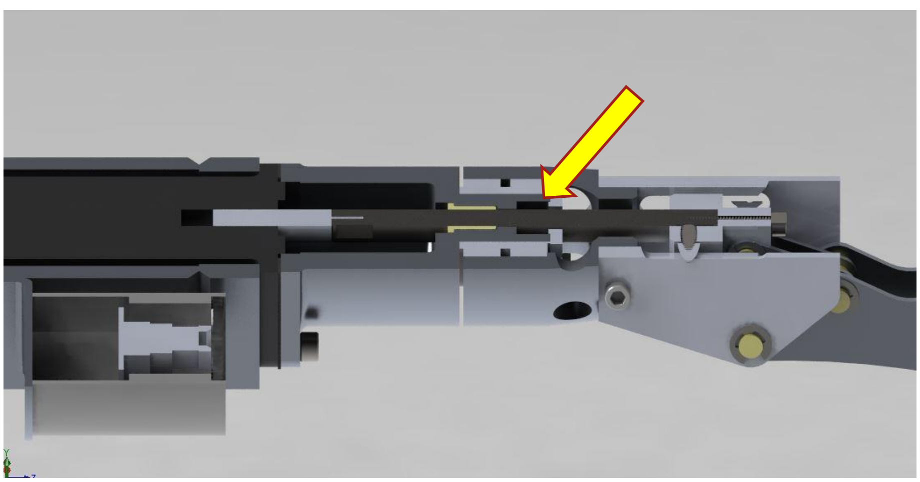


Figure 11: Cross section of Manipulator

The mechanical construction of the manipulator utilizes various materials that were selected for their performance and compatibility with arctic marine environments. 6061 Aluminum was the choice alloy for the custom machined components because of it's machinability, corrosion resistance, and wide availablility. Also, it can handle much a greater temperature range than it will be subject to in our application. All fastening hardware on the manipulator is 316 stainless steel. As an austenitic steel, 316 exhibits a lower hardness and tensile strength than some other commonly used steel, but its superior corrosion resistance make it the optimal choice for this application. Delrin is a polymer that is used for the manipulator side plates that hold the jaws. This highly machinable, low friction, rigid plastic maintains its toughness down to -40 degrees C, and only absorbs about 0.1% water by mass after immersion over a day [Dupont]. Since the immersion time for this system would likely be in the order of hours rather than days, it was determined that Delrin would be able to handle submersion without significant dimensional change.

Elbow Gearbox and Case

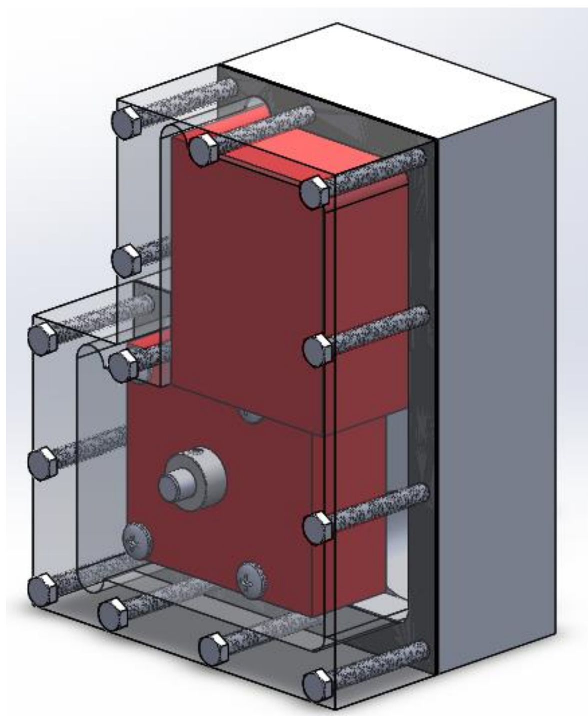


Figure 12: Elbow Gearbox and Case Assembly for Claw Movement

(This image is for reference throughout the following section)

This component is necessary for the pivoting of the manipulator about its elbow joint. The design process for the worm gear casing began with the gearbox itself. The Gearbox was selected for fitting a myriad of constraints. These constraints are as follows, in order of importance; output torque, position control, cost, and ease of implementation. The NEMA 23 motor is ideal because of stepping control, however the output torque from the stepper motor alone is only 100 oz in. For the motor to move the claw this torque would be insufficient. The worm gear box corrects for this with a 30:1 gearing ratio making the final output torque of approximately 21 N-m. This can easily handle the torque due to the weight of the claw, as well as any manipulation the ROV is required to perform. The second requirement, position control, is inherently dealt with by the stepper motor. The configuration of a stepper motor allows the output shaft to be rotated by stepped intervals. Each step is a known degree of rotation allowing the stepper motor to rotate a set amount within the resolution of the steps. For this project, one of the goals was to keep cost low. The gearbox that was selected, was purchased for the purpose of proof of concept. Because of this it was not required that the gearbox be an inexpensive and commonly available part. This is based on the assumption that if the ROV goes into production a custom gearbox solution will be required. Accounting for these assumptions the gearbox that was chosen is a surplus part, and therefore extremely inexpensive in comparison to the majority of similar solutions on the market. The gearbox fitting these criteria makes it a nearly perfect fit for driving vertical rotation for the arm and claw assembly, with one minor flaw. This gearbox is not designed for marine environments.

To prepare the worm gearbox and stepper motor for being submerged, a watertight enclosure was designed and fabricated. The enclosure, above all had to be watertight and able to withstand forces transferred to it from the claw. It also had secondary requirements of being compact, lightweight, and modular. These specifications produced a milled aluminum clamshell style case for the system. Aluminum was chosen for a material because of two preferential properties. Aluminum’s machinability makes it the ideal choice for the complex form of this part. The second property that makes aluminum ideal for this application its corrosion resistance. During the competition the ROV will experience a variety of harsh environments, one of which is a salt water. For the ROV to function in this environment without parts oxidizing it is imperative that corrosion resistant materials are used. Aluminum also nicely lends itself to the first two the secondary requirements. Aluminum’s high strength to weight ratio allows each part of the case to use a minimal amount of material and still be rigid enough to withstand the loading applied by the claw. Figure 13 and 14 display the two halves of the case.

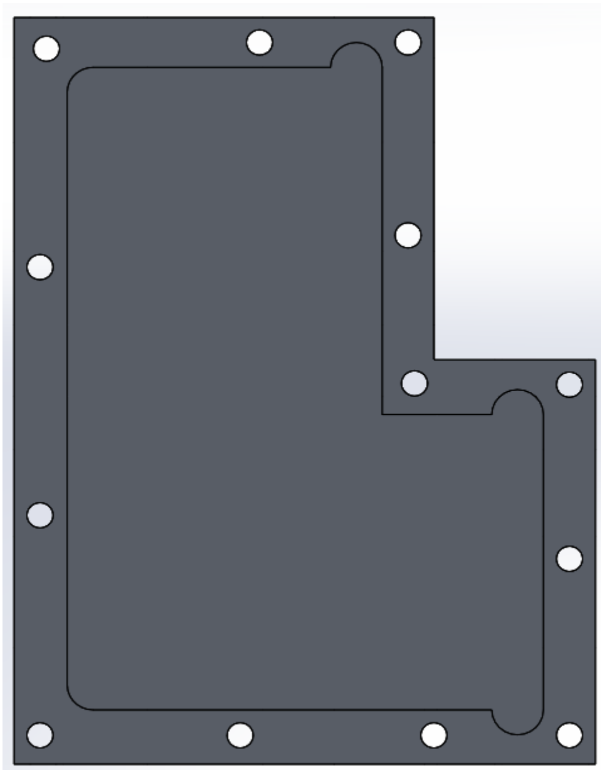


Figure 13: Gearbox casing left

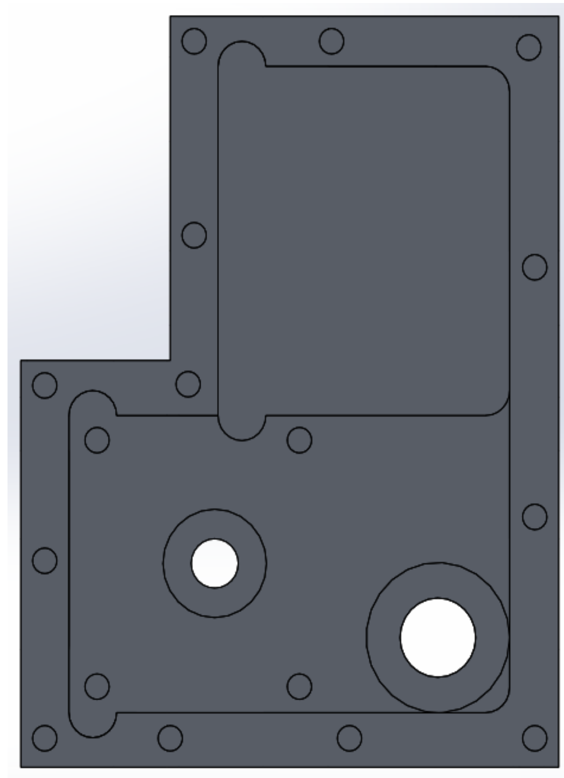


Figure 14: Gearbox casing right

The case has two output holes on the right half of the case. Both are oriented on the same face to make machining and mounting the case easier. The larger hole on the bottom right of the figure is for a watertight bulkhead and cable connector. This allows for the modularity of the case and gearbox assembly. Having this standard connector theoretically allows the assembly to be used for any application where a watertight high torque motor is necessary. The smaller hole on Gearbox Case Right is for the shaft output from the worm gearbox. Figure 15 is a cross section of the output shaft.

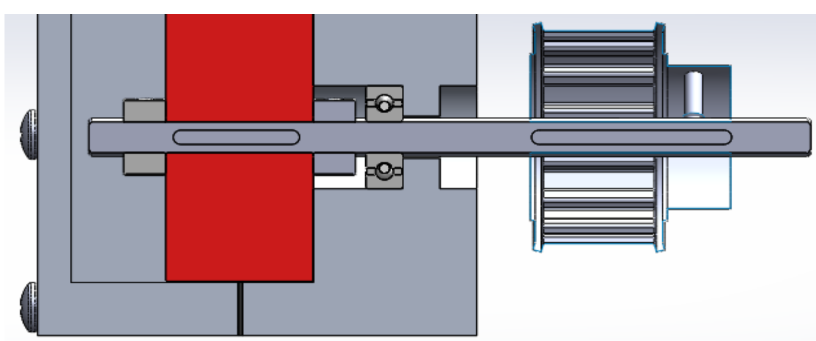


Figure 15: Cross section of Gearbox Output shaft

The image in Figure 15 depicts the cross section of the complete gearbox case assembly, focusing on the output shaft, moving along the shaft the components are as follows: shaft collar, gearbox, shaft collar, ball bearing, space for shaft seal, and the timing belt pulley. The purpose of the two shaft collars is to ensure that the shaft does not move linearly. The tolerance for concentricity of the shaft seal is approximately +0 / -0.0035 in. This means it is critical that the shaft is held nearly perfectly on center in reference to the shaft seal. The ball bearing that is press fit into the gearbox case accounts for this and ensures concentricity. The timing belt pulley serves as the method of power transfer between the gearbox case and the claw elbow. The pulley selected is rated to deliver the full approximately 21 N-m of torque from the gearbox to the claw elbow.

Measuring System

Figure 16: Roller Measuring System

This system was developed as a fixed attachment to the frame of the ROV created in order to measure the various lengths of the field objects. We designed this roller mechanism through the attachment of an encoder via a magnetic coupling device. They way this device works is by knowing the diameter of our roller and how many increments of the encoder amounted to one revolution. Using this information we are able to convert the number of increments into a particular distance that can be as precise as 40 microns if necessary.

The design of the system is through a stable connection between the roller and the encoder with the use of a belt and a magnetic coupling. The specifics regarding the magnetic coupling involves the creation of a device where the magnetic field generated by the magnets is used as a method of connection between the separate entities. It was necessary to use magnets capable of a maximum of 18 kg of force each since that maximum force decreased to just about 2 kg of force when spaced approximately 12mm apart. A total of four magnets were used with a two plates holding two each and fixed in a way so that the the plate could rotate but could not move any closer to each other. The magnets were also arranged on each plate so that one was two magnets with the North direction facing up while the other was South. By placing one plate inside of a water tight housing and then the other outside of the housing, the opposing forces attract each other and makes it possible for the axle attached to the encoder to spin as the roller spins on a surface.

Safety

During manufacture of the ROV, safety precautions were taken during every step. Proper eyewear was worn at any stage where debris of any form could become airborne. Also, the buddy system was always used while running machinery, etching circuit boards, and carrying large loads to ensure safety.

The design of the ROV contains various safeguards against potential injury. Any point along the HDPE frame is safe and easy to grab and is out of the way of the thrusters. In the case that a body part or object came in contact with the thrusters it would be protected by the cowlings surrounding the blades.

Electrically, all wires and connection points are fully insulated and water proofed to remove any chance of electrical shock. The tether itself is secured to the frame to provide strain relief, and to further ensure connection of all electrical conductors.

Challenges

Perhaps the greatest problem that the team faced was the number of issues we ran into while dealing with water proof electrical connectors for the tether-housing connection. These connectors proved to be difficult to source all on one place, and once sourced, were incorrectly shipped by the supplier. Upon discovering this, the problem was discussed with the supplier two more times and the wrong part was shipped again repeatedly.

To make things worse, it was also determined that assumptions were made about the function of some of the connector pins that resulted in having a permanently attached tether. This defeated the purpose of having connectors in the first place so then it was decided to include inline connectors. This caused a degree of redundancy that was excessive but necessary given the situation.

Skills Learned

Dynamic and static sealing techniques
Design for Manufacture
Printed Circuit Board Design and Manufacture

Programming in Java
Developing a GUI
FEA analysis
Flow Simulation
3D Rendering
Team Communication
Machine Shop correspondence
Compiling a comprehensive Bill of Materials

Future Improvements

Housing

The advantage to this design is that it avoids the use of internal holes within the housing for sealing so there is minimal potential for a water breach. All holes leading into the vessel are strictly for watertight connectors designed to keep water out. However, with the connectors and materials chosen, we are limited to the depths we can reach with the ROV. Although our goal was to reach 100 feet, we are limited to that depth due to the design if we wish to travel deeper. In future designs, further material analysis must be performed to find a material more suitable for a deeper depth as well as other potential means of creating a watertight housing for electronics. Also, the end cap design is not very simple to manufacture due to its awkward size and radial grooves. This design can certainly be perfected to allow for easier manufacturability and reproducibility. After the completion of the electronics, it was discovered that the size of the housing could have been reduced to a smaller size which in turn would have made the size of the entire ROV smaller. This would have reduced cost and complexity of manufacture. In the future, closer attention will be paid to the electronics first since this dictates housing size.

Chassis

The chassis design is very simple due to its skeletal-like design. There is not much material surrounding the housing yet it provides a rigid structure with a vast amount of mounting options for thrusters and other tools. The materials are inexpensive and easy to machine which makes this design very desirable. One factor that was not exactly considered was wire management throughout the outside of the ROV. Since there isn’t much excess material in the chassis, we are limited to areas in which wires can be routed without affecting the performance of the ROV. If wires were to be floating around, there is a chance for them to be severed by an outside force, potentially rendering the ROV immobile. In future designs, more thought would be put into wire placement which could result in the addition of chassis material or an entirely new chassis design.

Manipulator

There is significant room for improvement to the current design shown in **figure to the left** in terms of hardware selection and mechanical design. One of the weak zones for the manipulator is the output torque of the rotary stage of the DMA. While the 50 oz-in of torque is more than necessary to rotate the valves in the competition, it would likely not be adequate to rotate large valves in actual undersea pipelines. The amount of rotary torque that could be applied without rotating the whole ROV is roughly equal to the reaction moment that can be applied by the thrusters about the vertical axis of the ROV. Five pounds of thrust per thruster, multiplied by four thrusters at approximately 1 foot from the center of the ROV totals 20 foot pounds of torque. Considering this as a rough upper limit for torque output of the actuator that leaves room for about 77 times improvement from the current torque capability. To approach this limit, a sliding planetary gear assembly could be added to the output shaft, or a custom DMA could be manufactured from more powerful steppers.

Gearbox and Case

The current design for the elbow and gearbox case is for prototyping purposes only. The major benefit to this is that the case can be relatively easily modified. This allows the current prototype to have a versatile future. There could be a design in where the mounting solution for the gearbox case is completely different than the current one. The current prototype would be perfect for that, as the case could simply be modified to whatever form is needed. However the current design is bulky and heavy.

A design that was explored and could be perfected in the future was a hybrid case made of a polymer and aluminum for structural rigidity. This design could be employed as a final stage prototype. The benefit of the hybrid case would be to cut down on cost, machine time, and weight. The issue with this method manufacturing the case, would be that the design would be very specific to each situation. This would greatly deteriorate the modularity of the gearbox case.

While this versatility is fantastic for prototyping, it is far too expensive and time consuming for real production use. If the ROV were to become a commercially sold product an entirely new solution would be necessary. The current concept for such a design is to develop a gearbox that would be internally waterproofed. This would eliminate the need for the bulky aluminum case that the prototype utilizes.

Reflections

The undertaking of this competition has proven to be both a great challenge and opportunity. The mission tasks presented can be incredibility difficult, but it is always an enjoyable experience to spearhead the development of new and interesting technology to accomplish things in ways that may not have been possible before. The skills learned while developing the ROV for the MATE competition are highly applicable to industry and provide a serious speaking point at interviews for jobs.

Project Costing

Wentworth MATE ROV 2015				
Wentworth Institute of Technology				
Boston, MA, 02115				
Total	**$**	**4,611.28**		

PART	Quantity	Cost	Parts Total	ROV Component
T100 Thruster	6	$ 134.00	$ 804.00	Housing/ Chassis
80/20 aluminum	1	$ 31.59	$ 31.59	
shaft collars	16	$ 8.26	$ 132.16	
aluminum rods	2	$ 12.57	$ 25.14	
angled brackets	8	$ 4.56	$ 36.48	
Fasteners	2	$ 15.25	$ 30.50	
6061-T651 Aluminum Plate	2	$ 94.01	$ 188.02	
10" acrylic tube	1	$ 172.60	$ 172.60	
6061 alum sheet 1/8"x6"x24"	1	$ 14.81	$ 14.81	
1' long, 0.25" wall, 2.5"x2.5"alum tube	1	$ 30.55	$ 30.55	
Buna Quad ring	1	$ 12.00	$ 12.00	
Buna-N rubber sheet	1	$ 8.77	$ 8.77	
Shaft collar	2	$ 1.95	$ 3.90	
sheet of polyethylene	1	$ 28.36	$ 28.36	
Dual Motion Actuator	1	$ 343.25	$ 343.25	Manipulator
1"acetal bearing	2	$ 6.52	$ 13.04	
1' 6061 alum stock (3 1/8") dia	1	$ 69.44	$ 69.44	
Buna-N 12"x12" sheet (60A medium hard)	1	$ 9.51	$ 9.51	

Buna-N 12"x12" sheet adhesive back (60A medium hard)	1	$ 17.88	$ 17.88	
Lubrication-Free Acetal Ball Bearing, Glass Balls, 1/4" Shaft Diameter, 3/4" OD, 9/32" Width	6	$ 7.55	$ 45.30	
08 x 22 x 07ADL-PNBRshaft metric nitrile rubber covered steel	2	$ 5.37	$ 10.74	
MTO oil seal solid nitrile with a spring energized sealing lip in the single lip design	2	$ 39.38	$ 78.76	
polyethylene bar 12x2x0.75"	1	$ 10.63	$ 10.63	
MTO oil seal solid polyurethane with a spring energized sealing lip in he single lip design	2	$ 42.21	$ 84.42	
.625" thick, 3"x12"	1	$ 18.14	$ 18.14	
Delrin sheet 3/8" thick, 4"x24" (white)	2	$ 15.72	$ 31.44	
RX038DCB-N52	8	$ 12.98	$ 103.84	
RX84X8DIA	1	$ 74.88	$ 74.88	Optical Measuring System
AX2C45-N	2	$ 8.32	$ 16.64	
AX2C45-S	2	$ 8.32	$ 16.64	
clear circular glass	5	$ 8.18	$ 40.90	
Camera	4	$ 31.95	$ 127.80	Cameras
thick walled PVC	1	$ 12.04	$ 12.04	
40 pin plug	1	$ 16.19	$ 16.19	
size 4 sealed backshell	2	$ 16.42	$ 32.84	
18 pin receptacle	1	$ 17.01	$ 17.01	
18 pin plug	1	$ 25.74	$ 25.74	
size 3 sealed backshell	1	$ 14.11	$ 14.11	
#16 clipper male contacts	100	$ 3.51	$ 351.00	
#16 clipper female contacts	100	$ 0.73	$ 72.90	
40 pin receptacle	1	$ 17.75	$ 17.75	Waterproof Connectors
10 pin plug	3	$ 9.16	$ 27.47	
10 pin receptacle	3	$ 6.93	$ 20.80	
18 ga socket	2	$ 10.27	$ 20.55	
18 ga pin	2	$ 4.28	$ 8.55	
2 pin receptacle	1	$ 10.87	$ 10.87	
2 pin plug	1	$ 11.39	$ 11.39	
6pin receptacle	1	$ 11.26	$ 11.26	
6pin plug	1	$ 14.30	$ 14.30	
Aluminum Blocks 6x6x1.75	2	$ 46.10	$ 92.20	Gear box housing
316 stainless button head 4-40, 1/4" long	1	$ 2.77	$ 2.77	
standoff 3/4" long 4-40 thread	3	$ 0.51	$ 1.53	
standoff 1" long 4-40 thread	3	$ 0.60	$ 1.80	
standoff 5/16" long 8-32 thread	3	$ 1.48	$ 4.44	hardware/tools
socket head cap screw 3/4" long 8-32 thread	1	$ 4.00	$ 4.00	
retainer rings 316 stainless	1	$ 5.75	$ 5.75	
6061 alum tube 6" long, 4"x4"	1	$ 25.27	$ 25.27	

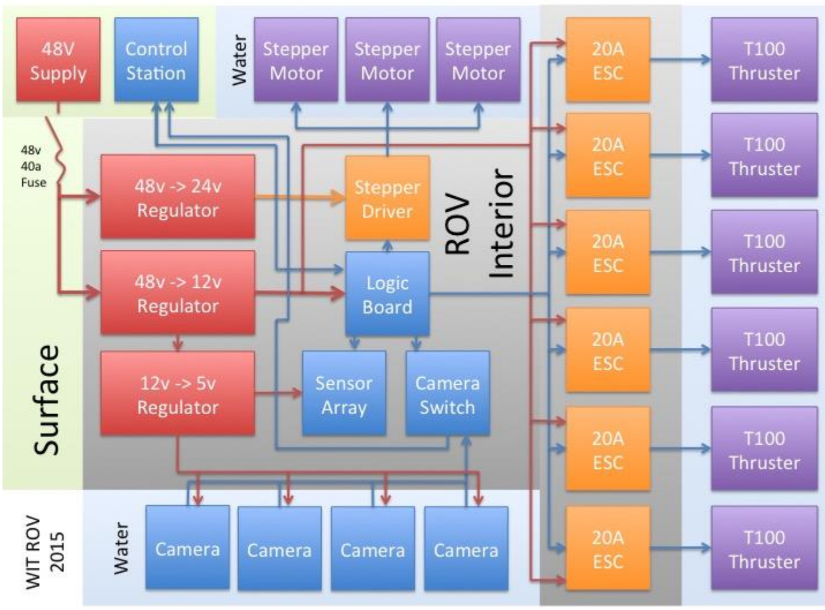
316 Stainless Set screws	1	$ 5.78	$ 5.78	
Head Cap screw 7/8" long	1	$ 8.36	$ 8.36	
Head Cap screw 3/16" long	1	$ 3.78	$ 3.78	
1"acetal bearing	2	$ 6.52	$ 13.04	
hex head bolts	2	$ 5.67	$ 11.34	
1" Dia Delrin Rod 1' Length	1	$ 4.90	$ 4.90	
80/20 hardware	10	$ 4.27	$ 42.70	
head capscrew 1 5/8" long 3/16" shoulder screw, 316 stainless	2	$ 12.14	$ 24.28	
316 stainless 8-32 full threaded 2" long	1	$ 11.43	$ 11.43	
316 stainless 8-32 locknut	1	$ 8.49	$ 8.49	
stainless screws	15	$ 1.61	$ 24.15	
Square End Mills	Mill Diameter (Inch): 3/8	1	$ 30.89	$ 30.89	
Voltage Regulators	10	$ 18.59	$ 185.90	Electronics
Ethernet Shield	1	$ 9.56	$ 9.56	
Stepper Controller (5 pc)	1	$ 15.00	$ 15.00	
LEDs (10 pc)	2	$ 7.61	$ 15.22	
2 Channel Relays	2	$ 4.79	$ 9.58	
Gyro	1	$ 34.95	$ 34.95	
Compass	1	$ 149.95	$ 149.95	
Temp/Humidity (5 pc)	1	$ 8.98	$ 8.98	
Depth Sensor	1	$ 59.95	$ 59.95	
40-pin long female headers	5	$ 2.84	$ 14.20	
40-pin long male headers	3	$ 1.50	$ 4.50	
25 gangable screw terminals	1	$ 7.95	$ 7.95	
Arduino Mega Protoshield	1	$ 14.95	$ 14.95	
Bidirectional Logic Converter	6	$ 2.95	$ 17.70	
Dehumidfying Canister	2	$ 6.81	$ 13.62	
Rotary Encoder	1	$ 39.95	$ 39.95	
Attiny84	3	$ 2.95	$ 8.85	
Laptop Warmer	1	$ 13.32	$ 13.32	
Hand Warmer	1	$ 19.94	$ 19.94	
100ft Cat6a Ethernet Cable	1	$ 24.99	$ 24.99	
100ft Shield Dual RCA Cable	1	$ 29.36	$ 29.36	
100ft 10AWG Power Cable	1	$ 38.99	$ 38.99	
10W 15ohm resistor x2	5	$ 8.99	$ 44.95	
10W 15ohm resistor x10	1	$ 12.19	$ 12.19	
40-pin std female headers	1	$ 3.98	$ 3.98	
40-pin std male headers	1	$ 4.99	$ 4.99	
DB-25 Male x5	1	$ 7.46	$ 7.46	
DB-25 Female x10	1	$ 9.20	$ 9.20	
DB-9 Male x2 Vertical	3	$ 3.39	$ 10.17	
DB-9 Male x10	1	$ 4.98	$ 4.98	
DB-9 Female x10	1	$ 4.99	$ 4.99	
0-ohm jumper x25	4	$ 4.50	$ 18.00	
14-pin IC socket x20	1	$ 2.99	$ 2.99	

LED x40	1	$ 5.00	$ 5.00	
LED Bar	1	$ 3.00	$ 3.00	
Resistor Assortment x1280	1	$ 8.90	$ 8.90	
Ribbon cable + connectors	1	$ 9.45	$ 9.45	
1uF Capacitor x10	1	$ 3.49	$ 3.49	
10uF Capacitor x25	1	$ 2.89	$ 2.89	
Solid Core Jumper Wire x70	1	$ 6.95	$ 6.95	
3.3v Regulator	5	$ 1.95	$ 9.75	
Photocoupler x2	6	$ 3.84	$ 23.04	
Transducer	1	$ 19.95	$ 19.95	
Decoder x25	1	$ 6.25	$ 6.25	
Shunt jumper x100	1	$ 7.50	$ 7.50	

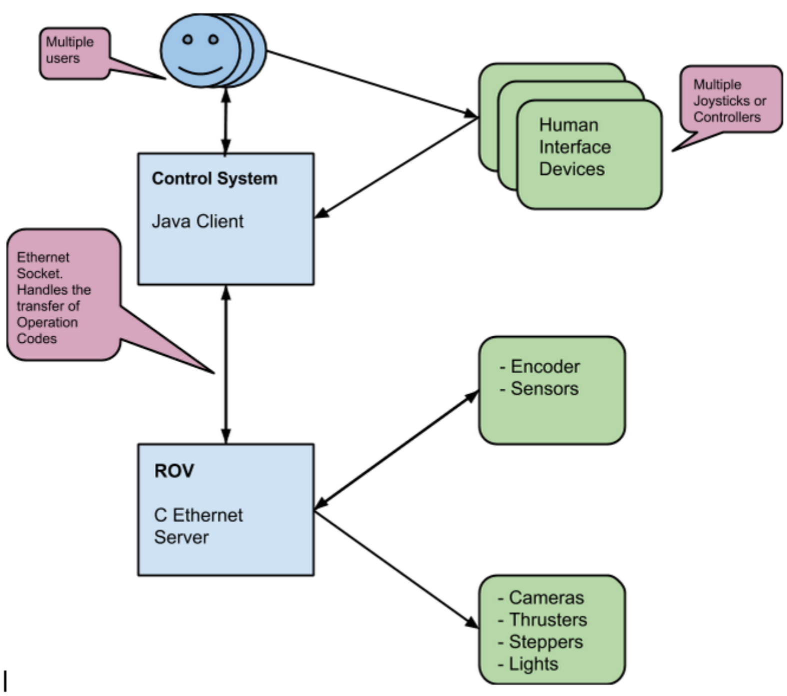
Budget

Our budget was defined by the amount of money that was donated to our team from various sources which totaled $5225.00.

SID



Flow Chart



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