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Ethics Statement and Signatures

The work submitted in this B.S. thesis is solely prepared by a team consisting of Ryan Wright, Daniel Martinez and Edgar English, and it is original. Excerpts from others' work have been clearly identified, their work acknowledged within the text and listed in the list of references. All of the engineering drawings, computer programs, formulations, design work, prototype development and testing reported in this document are also original and prepared by the same team of students.

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Abstract:

This project is an attempt to develop a Remotely Operated Vessel (ROV) for underwater exploration. To provide some guidelines this ROV is being developed according to the Marine Advanced Technology Education (MATE) competition requirements, with emphasis on being able to freely improve the dynamics of this particular design. The requirements being attempted include surveying, research, and recovery of objects. Design constraints will primarily be concerned with providing power to the ROV from the surface, maintaining dimensional constraints and being able to reach a predetermined depth. With the growing applications of ROV's on a daily basis and the scope of their requirements, considerations in the development of this project are being focused towards maintaining a minimal cost and increasing the ability to freely modify the ROV to include other tasks within their potential to assist in reducing the need to invest in multiple ROVs.

1 Introduction

1.1 Problem Statement:

This project is being designed to compete in the MATE ROV competition in the Explorer (Advanced) class. The ROV being designed must be capable of performing tasks such as identifying and surveying a shipwreck based on evidence found within the structure, collecting biological samples, replacing sensors underwater, and recovering objects such as litter.

These tasks are grouped with other minor requirements and a time frame of 15 minutes to complete each task. This project is being developed to complete all of these tasks with the consideration of being able to modify the platform slightly to add more applications to the capabilities of this design. With retaining a modular design future tasks can be added to the ROV's capabilities.

1.2 Motivation:

The motivation to design an ROV comes from the fact that as engineers we are constantly trying to push the development of technology. With ROV's there is already an established industry which has many opportunities for growth and bettering the understanding of our underwater environment. Part of the reason much growth is possible comes from the fact that many of the instruments used are industry specific with minor attempts at expanding the applications for these tools. ROV technology is still relatively new due to the fact the operating environment is within water causing communications and waterproofing issues. This project requires a collective use of the engineering knowledge attained such as Fluid Mechanics, Mechatronics, Materials, Mechanics of Materials, Manufacturing and Dynamics. With the applications of this knowledge our design will be effective and successful. The combination of the designers on this project also fuels the motivation with experience from scuba diving and the Navy.

1.3 Literature Survey:

Underwater exploration has centuries of history, with the greatest strides occurring during the mid to late 20th century. Originally diving bells were utilized for early underwater exploration dating to the late 1600's. These devices are rigid bell shaped structures with an opening in the bottom that are submerged with an observer. Due to the volume of air contained within these structures they must be dense enough to be negatively buoyant to allow the structure to submerge. These structures would also suffer compression of the air based on the atmospheric pressure increasing by 1 ATM per 10 meters or approximately 33 feet. In the late 1700's John Smeaton discovered a way to feed fresh air into the bells to allow longer potential times underwater and to prevent having to refill the diving bells with air.[12]

Submarines on the other hand, were first conceptualized in the late 1500's and were first attempted with minor accounts in the early 1600's. These systems were essentially diving bells with manual ballast systems of weights or valves to partially flood the hull to allow them to submerge and implement propulsion systems ranging from paddles to screw style propellers. These systems had no air systems which would cause the crew to have to surface frequently to avoid carbon dioxide poisoning due to the consumption of air by the occupants. To enhance the fluid mechanics associated with these hulls they slowly began to conform to the standard torpedo shape often associated with conventional submarines. From the early 1700's until the mid 1800's, submarines were powered by people and utilized natural pressure that was within the hull until it was submerged.[13]

At this point submarine technology became more standardized with having the conventional torpedo shape and many efforts to extend underwater times for purposes of war and research. Based on technologies growing for air compressors, propulsion system improvements, structure improvements and developing an understanding for the pressure effects of water at various depths by the 1900's underwater times for submarines were capable of exceeding an hour. Because of the risks and essentially unidirectional operation of submarines it becomes apparent that ROV technology has a place in underwater research. Since ROV's do not place people in the water risk is significantly reduced and physical limitations of the human body are no longer a factor. These systems however have a different design objective with trying to increase mobility underwater to allow the operator to maneuver more critical places. Because of this ROV's tend to be minimized for overall dimensions rather than streamlined for a single direction of movement. Due to the amount of motors needed to provide thrust accurately and in many possible directions to maximize movement potential, the overall dimensions of the ROV can potentially grow to massive dimensions. With adding many thrusters to maximize movement potential and adding many accessories to assist in conducting research the communications systems have a relatively high requirement which significantly limited ROV development.

In 1982 ROV technology began to take form due to advances in fiber optic communications and robotic control systems. The motivation to push for ROV development brought many benefits to underwater exploration. These benefits range from extended times conducting research and reduced risk involving diver injuries.[5] Historically ROVs have had a vast area of applications, but each ROV is specifically built for a particular task set. In the 1990's *Ventana* (Figure 1) was utilized to study offshore fault lines along the Pacific and North American tectonic plate lines. It is configured with a hydraulic drill and a storage compartment to enable rock collection and has multiple camera attachments to increase the observation potential.[3] Due to its robust design *Ventana* still is utilized with oceanic surveying many years after its primary design.

Figure 1: Ventana ROV [10]

Okeanos Explorer is used for exploring shipwrecks and utilizes an ROV rated for approximately 3.72 miles depth. This ROV is nearly 10 feet by 10 feet in dimensions and includes a manipulator arm.[4] The Navy utilizes the SeaFox (Figure 2) and other ROVs to run more accurate sonar and video feed back of potential mines to the operating ship to assist in neutralizing ocean mines. This application helps make shipping lanes throughout the world safer.[6]

Figure 2: SeaFox ROV [6]

Primarily the MATE competition recommends *Underwater Robotics: Science, Design & Fabrication* by Moore, Bohm and Jensen. This textbook serves as a well thought collective representation of many design considerations in developing many ROV's from simple Do-It-Yourself approaches to an introduction to some of the more complex systems utilized by various facilities.

1.4 Discussion:

Since ROV technology is relatively new and communications requirements are high their capabilities and costs are constantly changing. This can be attributed to an emerging hobbyist community and the required technologies constantly growing in their capabilities. Part of this team's goal is to develop a cost effective means of attaining an ROV to assist in expanding the various applications. Communication needs can be seen the fact that signal has to constantly be sent to each motor, video feedback must be streamed to the operator, and sensor feedback must be sent to the operator to provide information to the state of the ROV's hardware, and the environment constraints regarding depth and temperature at a minimum. Other considerations to the development of the design are the desired mobility potentials and potential atmospheres of the ROV.

2 Project Formulation

2.1 Project Overview:

Because of the emerging technologies affiliated with underwater exploration and the desire to explore the potentially unknown this project has a special interest within the team. The team is seeking a method for developing an ROV to attain a set of tasks and have potentials to be implemented in various industrial settings. Many design constraints must be accounted for through this project's development. Initially fluid mechanics is necessary to help guide development of electrical compartments and to help understand the reactions that will occur within the ROV and the body of water it will be operated. Second considerations must be made with dynamics, basic translational and rotational kinematics, and statics to assist in the development of the structure and determining requirements that help define the desired movements. Finally considerations for electrical components to be implemented and programming requirements must be considered. Because of the multidisciplinary requirements of the project it will push some of the capabilities of the team and result in a fully functional prototype that will hopefully help change some of the ROV technologies currently established.

2.2 Project Objectives:

This project is being designed to compete in the 2015 MATE ROV competition. With the guidelines given by the competition it is required that the design reaches a depth of approximately 30 feet. This design also must be capable of conducting basic underwater surveying through video from the ROV to the operator and object retrieval. This competition was determined as a viable option to generate a set of guidelines for the team to follow and establish basic objectives the team must be able to complete. In addition to completing these tasks our team has added personal objectives such as creating a modular design to increase the potential applications of the ROV. Additionally an attempt will be made to implement an easy to use control system to reduce complexities in ROV operation that requires specialized schooling often provided through the current manufacturers. One of our final personal goals is to keep cost at a minimum, currently basic observational ROV "Do It Yourself" Kits start at approximately $850 USD.

2.3 Design Specifications:

It was decided to develop the ROV for the MATE competition, but significantly expand the requirements to help push the ROV to potential commercial industries. To enter the various commercial settings the ROV must have a significant amount of power to counteract potential currents that the ROV may encounter during operation. Since some of the strongest ocean currents can be approximately 6.5 miles per hour it was determined to develop the ROV to operate at 3 meters per second which will be equal to about 6.7 miles per hour. This value gives the ROV slightly more power than the most severe ocean currents which will allow it to be able to slowly navigate upstream in the event of passing its desired operating region. In addition to the desired velocity the team wanted to be capable of reaching the deepest recreational diving limits. This depth is approximately 100 feet or 30 meters, which can only be visited for a few minutes at a time by divers without having to enter a decompression procedure. By being able to reach this depth it will minimize the requirements of divers visiting this depth and help increase research potentials.

2.4 Global Implementations:

Many considerations for our design were made with respect to the potential impact it may have globally. These range from the fact that with a low cost it is more easily accessible by small companies and countries with less financial resources then current people with ROV access. Additionally with the relatively low cost this particular unit can be thought of as essentially a minor loss upon catastrophic failure if it were to be implemented in hazardous areas. These attributes to this design will hopefully influence the market and the usage of ROV’s beyond the current demographic and will hopefully stimulate aquatic research since the required supporting technology is rapidly becoming cheaper.

3 Design Development

3.1 Conceptual Design:

Primarily the design thought process was guided by minimizing the effects of drag in a three dimensional operational field and enhancing maneuverability to ensure the ROV can freely move throughout a heavily constrained environment such as around reefs and within shipwrecks. Drag can be reduced primarily by minimizing the surface area normal to the direction of travel. Maneuverability can be increased by having multiple thrusters located throughout the design with positioning contributing to rotational and translational movement.

Secondary considerations are making the design modular and maintaining a low cost to make this product more easily attainable. To achieve a modular platform a skeletal frame was a primary consideration to allow many mounting points for various hardware configurations. With considering maneuverability and minimizing cost it was decided to have the ROV able to travel vertically and along a primary horizontal axis with turning controlled by two horizontal thrusters to enable turning by powering motors in opposite directions or varying speeds. By eliminating a sideways travel path additional thrusters are eliminated. This basic motion decided requires the use of three thrusters with additional thrusters for additional operational directions or rotations.

Other considerations are buoyancy, waterproofing electronics, operator feedback, gripper operation, and the control system. A neutrally buoyant design was determined to be ideal in order to minimize the operation of the vertical thrusters to maintain depth. In addition to the magnitude, the central point of buoyancy must be determined which will help the ROV maintain its natural underwater orientation. To keep the ROV upright it was determined to locate the center of buoyancy slightly towards the top region of the ROV with center of mass being slightly towards the bottom region of the ROV. To waterproof the electronics a pressure vessel must be designed which will provide positive buoyancy so location will be towards the upper region of the ROV, this will also help with the design having buoyancy properties similar to what the team is trying to attain. This pressure vessel must hold all of the required electrical components and upon researching the various controllers that may be implemented was decided to hold at least a 3 inch by 7 inch chipset. Operator feedback would have to require information relating to the status of the ROV, which would be moisture to monitor potential shorting, power status, depth due to pressure changes, and a camera to see where exactly the ROV is going. These sensors are a moisture sensor, a volt/ammeter chip, a barometer and a webcam. It was decided to house the webcam in a separate but similar pressure vessel as the other electrical components to add symmetry to the ROV and make the design requirements of the pressure vessels capable of being performed with one design and set of analysis procedures, which will help keep the location for buoyancy relatively close to the center of the ROV design. As the application of the gripper was assessed it was realized that it must be able to change its orientation to freely grab objects underwater, but movement of the gripper would require moving the camera. In addition to moving the camera the servo motors used to move the gripper would have to be waterproof which adds to more cost and complexity to the overall design. To overcome this, the decision to make the entire ROV tilt was made which required adding a 4^{th} thruster oriented in the vertical axis.

Based on being able to have a secondary vertical thruster the net thrust in the vertical axis can be divided between two thrusters. In addition an estimated cost of servos being approximately $70 for moving the arm versus $40 for an additional thruster makes this decision a potential feature to reduce expenses, which in turn makes the design proposal more lucrative.

3.2 Design Alternatives:

Decisions regarding thruster configurations are critical towards the operational requirements for an ROV. There are two primary orientations for the thrusters which are a direct drive, where thrust is directed normal to a surface, and vector oriented thrusters, where the thrusters are aimed at various angles from the ROV to propel the ROV in various directions operating by the sum of the forces creating a resultant force in the desired direction of travel. A comparison of these drive systems can be seen in Figure 3. Because of the added cost of multiple thrusters and the attempt to minimize cost this project was designed using direct thrusting techniques.

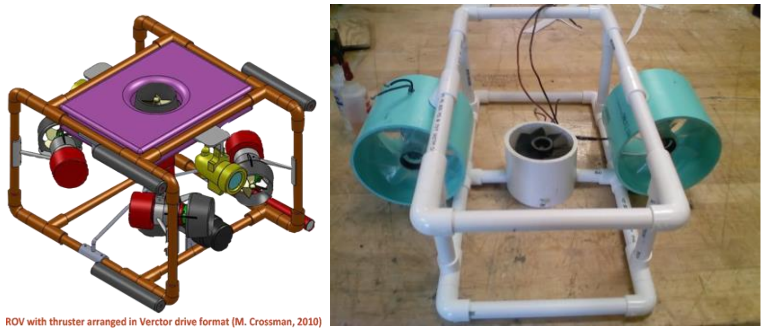

Figure 3: Comparison of Vector vs Direct Thrust [11][15]

As can be seen in Figure 3 basic horizontal propulsion and maneuvering can be attained by two thrusters with direct thrust and a lateral movement would be eliminated. By implementing 4 thrusters with a vector based thrusting system the magnitude of thrust in the various directions can add to an overall greater magnitude of thrust per similar sized thruster, and a lateral movement can be attained. Cost is a primary difference in the two methodologies with adding additional thrusters and propellers that made this design less likely for building a low cost ROV system. Additionally adding controls to balance the thrust in the desired locations and attempt to maximize the potential for the configuration would potentially be a difficult task. These factors guided the team in determining a direct thrust method would be the best potential candidate for adding to success of the ROV project.

The initial design was to reduce some maneuverability over typical commercial configurations by removing thrusters that are not required for basic operation. This design had three thrusters, one for vertical direction and two for horizontal, which critically saves component costs. When assessing this design with the required tasks it was decided that the gripper arm must be able to move. Because of this at least one additional waterproof servo is required and a secondary camera or a primary camera with a pan tilt feature would be required. Upon pricing components it was discovered that this would add an additional expense to the design and add additional failure points which contributed to deciding against this design. A similar concept is the OpenROV design in Figure 4.

Figure 4: OpenROV Kit [8]

When brainstorming a way to eliminate an entire manipulator arm from the design one configuration was discovered to enable the ROV to tilt with varying the thrust from the rear of the ROV. This design required four thrusters for horizontal movement and would require a 5^{th} for vertical control, which can be seen in a similar ROV pictured in Figure 5. Because of the potential for adding cost to the project and the possibility that controls may become difficult to configure, this design was eliminated. This design's operational means were saved and implemented towards the final design.

Figure 5: Multiple Rear Thrusters [9]

3.3 Proposed Design:

The primary design accounts for a vertical and a primary horizontal travel path, and accounts for rotating about the vertical axis and horizontal axis giving a significant amount of control to the operator. This was done by implementing a front and rear thruster in a vertical orientation and a right and left thruster in a horizontal orientation. By implementing the thrusters in this manner many capabilities of the ROV are still preserved and thruster requirements are reduced. The primary movement that is lost will be a lateral translation of the ROV, which can be important in some surveying scenarios but if a lateral effect is desired an additional camera can be installed and the ROV can capture images moving parallel to the ROV's operation to reduce the effects of this change.

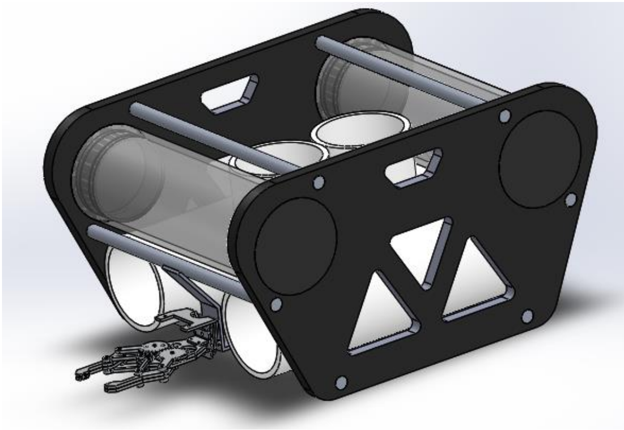

Figure 5: ROV design (Gripper from Grabcad)[7]

As seen in Figure 5, the white tubes are an arbitrary duct for thrusters to account for space from industry trends with smaller ROV thrusters. Once the thruster configuration was established, the electrical components were arranged and a frame was developed. This design accounts for arbitrary dimensions which allows the ROV many additional locations for mounting features such as onboard power, wireless communication, additional armatures for tasking, and additional sensors. Component configurations can be seen in Figure 14 (Appendix).

3.4 Global Design Considerations:

Focusing on design attributes to expand the scope of the project critical decisions were made early in the design development. Rather than staying firmly within requirements to successfully compete in a competition, the design focus was to build a highly versatile, robust design by extending the maximum operating depth to over 100 feet, speed potential that can counter some of the fastest ocean currents and retaining a modular design to expand the ROV to being able to be adopted easily by industry. By trying to reach a large market it was decided to implement an Arduino UNO for the main control interface. With the Arduino based chipsets, support can easily be found with relatively simple searches online. It is also one of the more open-source chipsets that will allow easy modifications to the system to allow for easy growth from the end user by allowing many additional user interface potentials on both the hardware and software sides of this system. This allows for development of software from many programming suites that can communicate via serial communication to the ROV and allows for an open source reference to the operating system.

Power considerations were made with implementing a 12V DC system. This enables power to be attained by simply attaching the ROV to a boat battery, car battery or power inverter if it is operating from a land based facility such as a marina or utility plant. The size for the ROV also allows easy transport because it can be carried by hand to areas that may be difficult to access due to other equipment in the way or no infrastructure for automobiles to reach the operating area. By retaining a small footprint for the device it also enables launching without a crane or specialized equipment, additionally reducing the operating expenses.

3.5 Control Software

In determining the best method to implement a control system for the ROV, several options were investigated. Primarily, due to the signal attenuating nature of water, the control system would require a wired hardline connection. Additionally, in order to allow a high level of customization and expansion, a system that is flexible was greatly desired. With these ideas in mind, selection of the control system went forward.

Initially, the use of a simple 6-channel RC control system, widely available for consumer purchase, was considered. As shown in Figure 6, this type of system consists of a transmitter and receiver pair, control signals being sent via a wireless radio or hard-wired connection. This method was deemed simple to implement yet not robust and quite expensive. It would allow for simple controls of the ROV but would not allow the implementation of sensors or advanced control algorithms. In short, it would render the ROV functional but greatly restrict any improvements or future work on the platform.

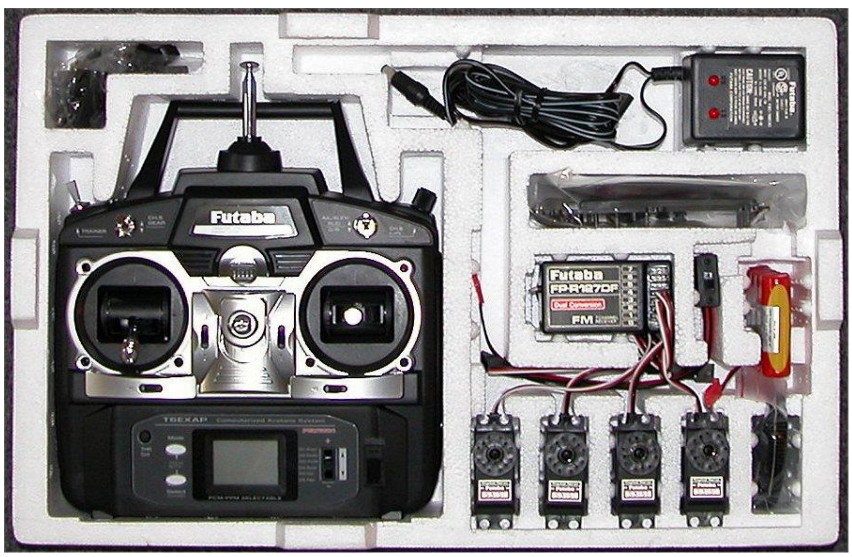

Figure 6 Futaba 6-Channel Control – [16]

Next, an open-sourced, software control system was explored. Developed by Chris Konstad initially as part of a Robotics Team at UC Berkley, Monterey ROV-Suite seemed a promising solution for our ROV control system. Written in Qt with SDL for joystick support, the platform boasted a high level of customization and expandability.

The software consisted of an expansive user-interface, shown in Figure 7, running on a laptop communicating with a small Linux based single board computer aboard the ROV.[17] Control signals were then relayed to microcontroller and executed.

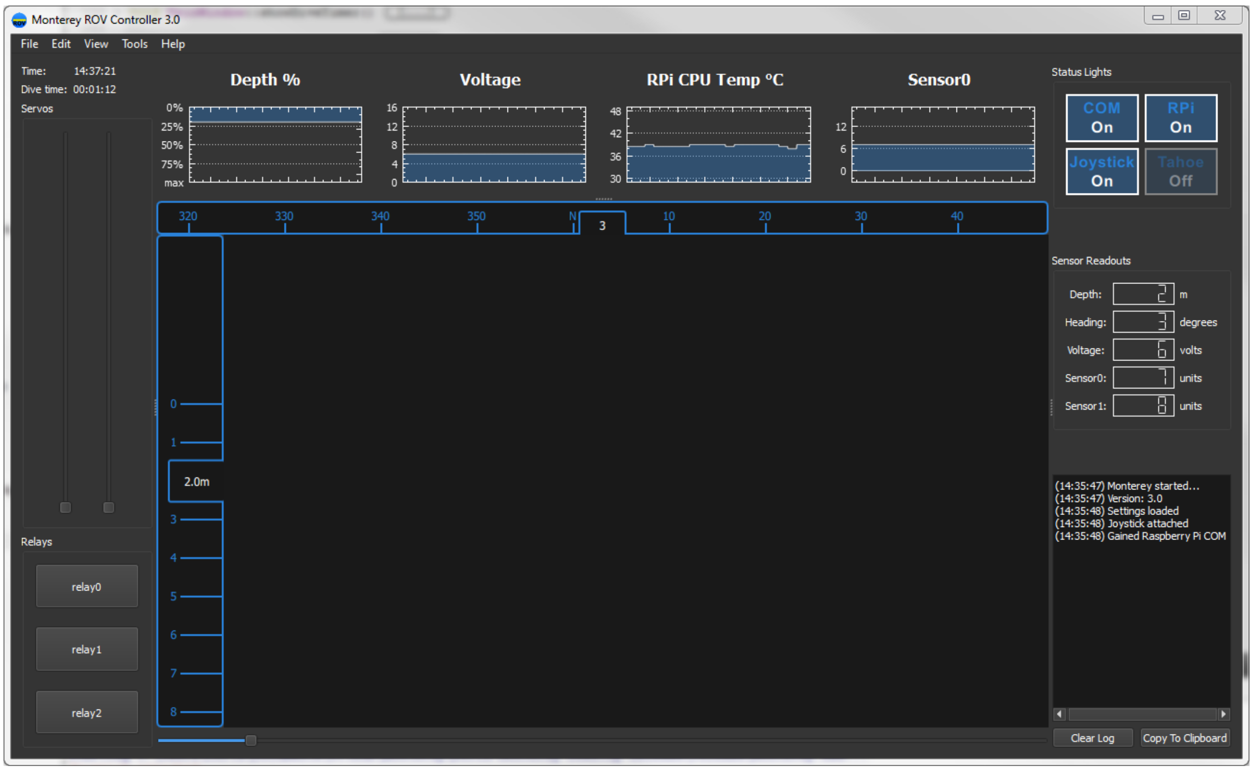

Figure 7 Monterey GUI [17]

Monterey seemed to be a perfect solution, unfortunately several issues arose during initial implementation. Primarily, the control suite was still under heavy development. We found that this resulted in incomplete and, sometimes, entirely absent documentation. This rendered the software very difficult to modify and make suitable for our system specifications. Additionally, the provided microcontroller code supported only specific sensor modules that were either very expensive or out of production and nearly impossible to obtain. Finally, the system required a Raspberry Pi onboard the ROV in addition to the microcontroller. Given the small size of our ROV, this added complexity to several aspects of the design, including spacing, power-distribution, and the addition of an extra layer to the control software. For these reasons, this control system was deemed too complex and difficult to implement in the given time frame.

MATLAB was then suggested as a possible solution. Research showed that MATLAB would easily integrate with an Arduino microcontroller via a provided support package. This package would allow for the microcontroller to listen for commands from MATLAB over a serial USB connection and then execute these commands or return results. The MATLAB programming environment would allow us to begin building the control software and provide useful development and debugging tools. Additionally, later work to add increased functionality and improvements could easily be implemented. Finally, MATLAB provided a coding platform that the entire group was familiar with and could work in. This was very beneficial as all the coding would be done in MATLAB and the microcontroller would only run the provided server code that would enable it to communicate with MATLAB and thus would require no additional coding.

3.6 Discussion:

Upon discovering a chassis configuration that would meet the basic levels of mobility and modular application it became evident that many of the objectives could easily be attained. Through preliminary studying of ROV structures and operational requirements, the team is confident that this structures design will be quite effective. Additionally by evaluating an existing ROV suite and applying past experience with programming, software was able to be assessed. The team feels confident in the abilities of a serial communication through MATLAB being able to successfully support operation of the ROV. Due to the fact that the ROV is being supported with a serial communication, other programming languages can potentially be applied to help further reduce the cost of operation or to possibly add more potentials of the ROV.

4 Project Management:

4.1 Overview:

Because of the various requirements needed to be achieved, work must be distributed and multiple disciplines must be approached in a systematic method. Being able to propel the ROV is a primary requirement therefore formulation of the propulsion system logically should be placed as the first objective. Upon being able to propel the system its supporting systems must be in place or the ROV will be rendered useless. Because of this, arbitrary brainstorming of the pressure vessels must also occur. Once these primary objectives are complete, the team can proceed with development of the various mounting systems to link the systems and fully define the structure. Analysis must be performed on the entire design to validate its function and determine if any revisions will be necessary. The analysis will provide insight to some of the behaviors that may occur within the system and will help validate some equipment requirements. At this point the ROV will be fully defined and integration of control systems can occur. Finally upon completion, testing can be performed to provide the team with results relating to how effective the design is compared to theory.

4.2 Work Distribution:

The development of the ROV consisted of many basic tasks. Primarily developing a method for achieving the desired mobility became a driving factor. This dictated the required trajectories the thrusters must be aimed. Upon developing a layout for the thrusters hardware mounting must occur. This includes defining some of the requirements of the implemented hardware and devising a method for effectively attaching them to the ROV with keeping a streamlined design. As arbitrary locations for thrusters and hardware were defined a basic template for the ROV will begin to take form and a more detailed design can occur based on the requirements the ROV must perform. Through the detailed design hardware was assessed for its availability and ease of implementation which established some of the desired fastener sizes, styles of pressure vessels were examined and basic industry practices were implemented to guide the rest of the design.

After design is completed analysis must be performed to help validate the decisions made and potential concerns must be assessed with minor revisions. This phase includes examining the drag of the design to determine the thruster requirements and if they are attainable. Analysis also includes analysis of the pressure vessels to make sure they are capable of being implemented at the desired depths. Beyond these primary factors stresses that will be applied from the thrusters must be translated to the chassis and the mounting solutions that are to be determined based on the thrusters that will be used.

Once analysis is completed purchasing of required components and construction can begin. With construction taking place any issues that may be presented can be addressed as test fitment is occurring and adjustments to the design may take place. This essentially active fit check will account for inconsistencies that may be discovered through purchased parts that may be out of specifications from the suppliers, blemishes that may occur in manufacturing, or manufacturing changes that may reduce cost and allow for easier manufacturing of the specialty components utilized in this project.

After manufacturing testing of the ROV will occur to help verify the theoretical potentials established in analysis. This testing will begin with checking the integrity of the electronics compartments. If the electronics compartments are not properly sealed catastrophic failure will be inevitable and the project will be unsuccessful. Upon verifying the pressure vessels are structurally sound the electrical system can be implemented and examined. After this both systems can be tested working in unison to determine that they will function together and will result in a successful project with minor adjustments to enhance the overall performance of the ROV.

4.3 Timeline:

To help guide the team to success an aggressive timeline was constructed to allow the team the opportunity to attain their goal in a timely manner if it is adhered to. Because of the nature of the timeline it accounts for and extensive testing timeframe that can be easily reduced if the project falls behind on schedule. These losses in effective working time can come from lack of work being conducted through the summer months due to possible internships or summer classes conflicting with the ability to perform research and development of the ROV, but under ideal conditions will allow for detailed analysis of testing results.

Table 1: Timeline for Project

	Jan-14	Feb-14	Mar-14	Apr-14	May-14	Jun-14	Jul-14	Aug-14	Sep-14	Oct-14	Nov-14
Project Formulation	■										
Initial Design		■									
Evaluate Initial Design			■								
Design Improvement				■	■	■					
Control System Selection			■	■	■	■					
Hardware Selection		■	■	■	■	■					
Construction					■	■	■	■			
Testing and Refinement								■	■	■	■

4.4 Work Distribution:

Since experience and proficiencies amongst the team is somewhat diverse it enables tasking to be delegated based on each team member's ability to perform the tasks while retaining the ability to gain assistance from the other team members. Research for defining design constraints, normal industry practices, and required computations is to be collectively done within the entire team. Formulation of the design objectives is dictated by the competition guidelines, but additional constraints are to be developed from what the team collectively feels would be beneficial to the advancement of ROV technologies on the limited budget since funding for this project is through the team further adding to the constraints of this project. Because of Ryan's proficiency with hobby based hardware and some proficiency with programming the hardware to function with a microcontroller hardware selection will be one of his primary responsibilities. With Daniel being most proficient in programming he will head that portion of the project. Collectively as a team detailed design development, analysis, construction and testing will be performed as a team.

Table 2: Team Time Log

Time Log per Team Member			
Task	Member	Time (Hr)	Total Time
Preliminary Research	Daniel & Ryan	4	8
Design Configurations	All	3	9
Drag Calculations	Ryan	2	2
Validating Drag	Daniel	1	1
Pressure Analysis	Daniel	1	1
Buoyancy Analysis	Ryan	2	2
Presentations	Edgar	2	2
Report	All	8	24
Control Systems	Daniel	20	20
Construction	Daniel & Ryan	9	27
Modeling Design	Daniel	2	2
Component Research	All	2	6
Testing	All	5	15
Total Time			121

4.5 Commercialization of Final Product:

Upon successful completion of designing the ROV the team plans to utilize it in the MATE ROV competition. This will generate exposure of the team to various ROV's and allow the team a setting that can allow a direct comparison of the performance and capabilities attained by other people researching within this field. If the ROV proves to be successful in attaining comparable or better operation potential as commercially available ROV's due to the expenses to develop it, potential marketing may occur with launching a kickstarter campaign to begin generating funds for additional developments that were omitted from concept development to reduce expenses. Due to the costs with purchasing commercially available ROV's the inflation on this particular design should be able to generate substantial revenue and provide a low cost alternative to currently available ROV's, which gives it potential commercial growth and further development.

4.6 Overview:

Through development of the structure and planning aggressively at the beginning of the project it can be seen that plenty of time is allotted to possible issues that may arise in scheduling or in the design and construction of the ROV. This scheduling will be intensive for the team to sustain through the beginning of the project however as the goal of developing a successful ROV is neared the schedule will progressively become less demanding and allow for intensive testing and additional developments if the schedule is successfully adhered to.

5 Engineering Analysis:

5.1 Analysis Overview:

To determine the integrity of the design and assist in defining component requirements analysis must be performed. Various simulations were implemented with computational analysis occurring to assist in validating the results. First external flow is required to determine reactive forces acting on the ROV in a flow stream at the desired maximum velocity. Thrust calculations were then implemented to determine motor and prop requirements to make sure that components are available to reach the desired outcomes of this design. Another critical concern is the evaluation of the pressure vessels to make sure they can sustain the desired depths. Because of the density of water it is known that for approximately 33 feet or 10 meters of depth 1 atmosphere of pressure is added. Buoyancy was also examined which will help guide the team in adding more mass or adding lift to the ROV. Beyond basic positive or negative buoyancy magnitudes fine adjustments of trim, the distribution of mass, will have to occur through testing. Additionally since calculations implement idealized materials fine adjustments to the magnitude of buoyance will be addressed with testing iterations. In addition to developing the basic structure hardware to interface all of the components must be created and tested. The final additional hardware required to complete the design would consist of motor mounts.

5.2 External Flow Analysis:

The primary structure and electrical housings were then imported to ANSYS CFX and SolidWorks Fluid Analysis and placed in a stream of three meters per second of water which provided the reactive force as a value of 130 N. This was also checked in ANSYS CFX which established 132 N as a reactive force at three meters per second. These values convert to approximately 6.7 mph and thirty pounds of a resultant force from the thrust.

Table 3: Forward Drag Simulation

Table Chart

Name	Unit	Value	Averaged Value	Minimum Value	Maximum Value	Progress	Use In Convergence	Delta	Criteria
GG Max Velocity (X) 1	[m/s]	3.184	3.129	3.029	3.184	24 %	Yes	0.125	0.030
GG Max Velocity (Y) 1	[m/s]	2.806	2.801	2.788	2.806	100 %	Yes	0.019	0.030
GG Max Velocity (Z) 1	[m/s]	4.703	4.697	4.678	4.743	68 %	Yes	0.065	0.044
GG Normal Force (X) 1	[N]	-0.228	-0.333	-0.740	-0.104	42 %	Yes	0.178	0.074
GG Normal Force (Y) 1	[N]	84.543	82.514	78.298	84.603	51 %	Yes	6.304	3.206
GG Normal Force (Z) 1	[N]	129.928	129.032	127.472	129.928	100 %	Yes	2.455	6.987
GG Force (X) 1	[N]	-0.223	-0.320	-0.725	-0.089	44 %	Yes	0.170	0.074
GG Force (Y) 1	[N]	84.088	82.042	77.822	84.142	51 %	Yes	6.320	3.206
GG Force (Z) 1	[N]	134.379	133.359	131.700	134.379	100 %	Yes	2.679	7.120

To validate the results the following drag calculation was performed.

$$F_d = 1/2(\rho * C_d * A * V^2) \quad \text{(EQ 1) Drag Force}$$

F_d = Drag Force

ρ = Density

C_d = Coefficient of Drag

A = Area

V = Velocity

Due to the results in ANSYS CFX being in metric the following calculations were conducted in metric units to validate the findings. With the projected frontal area equal to approximately 0.0298 m, a desired velocity of 3 m/s, and water density of 998 kg/m^3 and applying a drag coefficient (C_{d}) of 1, the required force is 133.83 N which is close to the simulation results. This study is not including the sloping edge or curved face of the cylinder that generates friction and utilizes a worst case scenario for drag on a basic rigid body. This value due to symmetry within the model is essentially double for vertical thrust required.

5.3 Thrust Analysis:

Thrust calculations were at this point to help establish an appropriate propeller sizing to correlate with the motors that are planned for use. Various propellers that are readily available were researched and the information was put into a thrust calculator which is based on static thrust equations with information from the motors and electronic speed controllers to define the motor performance.

$$RPM = Volt * Kv \qquad \text{(EQ 2) Conversion}$$

$$H.P. = \frac{Amps*Volts}{745.7(\frac{Watt}{HP})} \qquad \text{(EQ 3) H.P.}$$

$$F_{Thrust} = Density * A * Vel.* (Vel. - InitialVel.) \qquad \text{(EQ 4) Thrust}$$

Kv = Rating of motor

A = Area of stream

The various geometries were selected based on diameter and pitch. Then the propellers that would get closest to 15 lbs or 65 N were selected as potential candidates. With propellers identified as potential candidates cost became the driving factor for selecting the propellers that were used.

5.4 Hydrostatic Pressure Analysis:

In the design process for this project, it is of high importance to ensure that the vital structures of the ROV can withstand the hydrostatic pressures that such a vehicle will encounter when submerged at operating depth. For our specific design, only two structures will be required to withstand said pressures. The forward and aft components tubes, as seen in Figure 9, will contain all of the necessary control hardware for the operation of the ROV. As such, these two structures must maintain a water tight seal and be capable of withstanding significant hydrostatic pressure without failing.

The two enclosures must be analyzed as thick-walled pressure vessels, due to the fact that ratio of radius to wall thickness is greater than 1/20. Additionally, the interior of the enclosures will contain atmospheric pressure. Therefore, we will analyze the enclosures as capped, thick-walled, cylindrical pressure vessels under external pressure only. Using this analysis, the principle stresses are determined form the radial, tangential, and longitudinal stresses. The maximum shear stress is then determined at the inner and outer radii and the safety factor is then computed using Maximum Shear Stress Theory.

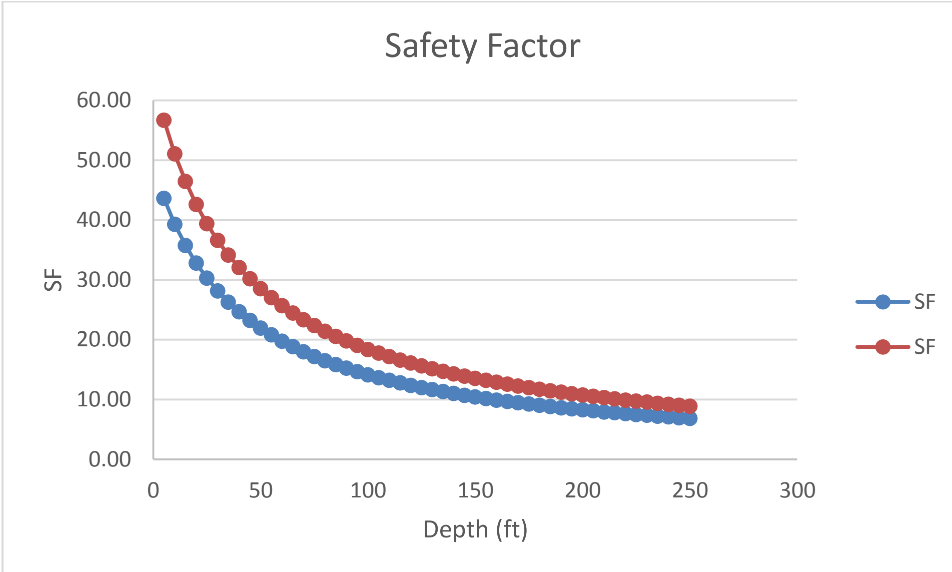

Figure 8: Hydrostatic Pressure Safety Factor

Figure 8 shows the resulting safety factor for the inner and outer radii versus depth. As shown, the factor of safety is smaller for the inner radius of the pressure vessels due to the increased stress on the inner wall. That said, the chosen material for the enclosures can easily withstand the expected operating depth of 30 feet. As shown, the factor of safety is 6.83 at a depth of 250 feet. This proves very promising for our applications.

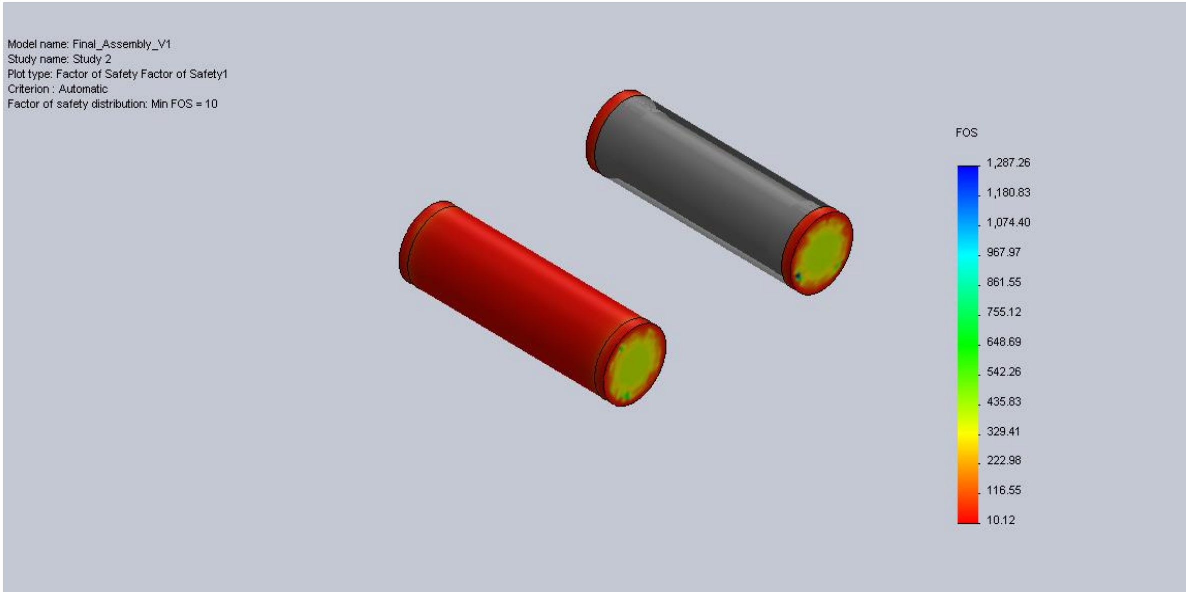

Figure 9: Pressure Simulation

In order to confirm the results of the calculations, a pressure test simulation was run via SolidWorks. Figure 9 shows the results of this simulation. As shown, the minimum safety factor for the enclosures was 10. The simulation was run using an applied external pressure of 330 kN/m^2 (0.33 MPa) or 47.86 pounds per square inch. This is the expected hydrostatic pressure at a depth of 70 feet, double that of our required operating depth. Clearly, the material and shape selected for the pressure vessel can easily withstand the pressures it will experience during the competition.

5.5 Buoyancy Analysis:

Beyond pressure the sub must be stable and relatively neutral in buoyancy. Because of this buoyancy calculations were implemented to determine the natural behaviors and account for revisions in potential iterations. The desired overall buoyancy for this sub is to be slightly positively buoyant. This is to allow for the sub to return to the surface upon failure. To calculate buoyancy the density and volume of an object must be multiplied and the mass of the object in relation to the volume displaced must be greater than the mass of water in that displaced volume.

$$Weight = Volume * Density \qquad \text{(EQ 5) Weight}$$

$$Buoyancy = Weight_{Displaced\ water} - Weight_{Rov} \qquad \text{(EQ 6) Buoyancy}$$

Table 4: Buoyancy Calculation

Units in inches and lbs weight						
Item	OD (height)	ID (Width)	Cross sectional area	Length (depth)	Volume	Weight
PVC elect	3.5	3.068	9.62	23	221.2859	2.7025
PVC duct	3.5	3.068	2.23	64	142.6221	7.52
AL Rod	0.5	11	0.20	69	13.54812	1.381908
Side Plate	15.5	8.5		1	76.28	3.251832
Hull Total					**453.7361**	14.85624
Motor/ESC/Claw/Arduino						1.5
Onboard Total Weight						**16.35624**
Displaced Water Weight						**16.34374**
Buoyancy						-0.0125

The above table takes into account the various geometries and the way their masses were capable of being calculated. Due to hardware being purchased and not having all of the required technical documentation easily accessible they were physically weighed with the displacement being approximated by aggressively rounding volumes in the other components. Based on the buoyancy being a slightly negative value it is accepted that it will be essentially neutral since the material properties are idealized and it may vary based on production tolerances within the material production and manufacturing variances. It will also be adjusted in the final steps of the project with additions of small floats or weights to more accurately trim the ROV to a horizontal positioning and being slightly positively buoyant overall.

5.6 Motor Mount Analysis:

In order to place the motors inside the thruster ducts, we needed to design a mount as no off the shelf solution was available. The mount geometry was designed as to allow the motor to be mounted, fit snugly inside the thruster duct, and allow a reasonable amount of flow through the duct. The material was initially selected to be acrylic as we had a small surplus from the materials for the side-plate construction. Given the unique geometries, a simulation was required to ensure that the mount could withstand the thrust force exerted by the motor and prop without failure. Figure 10 shows the result of the simulation. As shown, the minimum safety factor that resulted was 6 and fairly uniform over the entire body of the piece. Thus allowing us to move forward with the manufacturing of the mounts without the need to modify the design or construction material

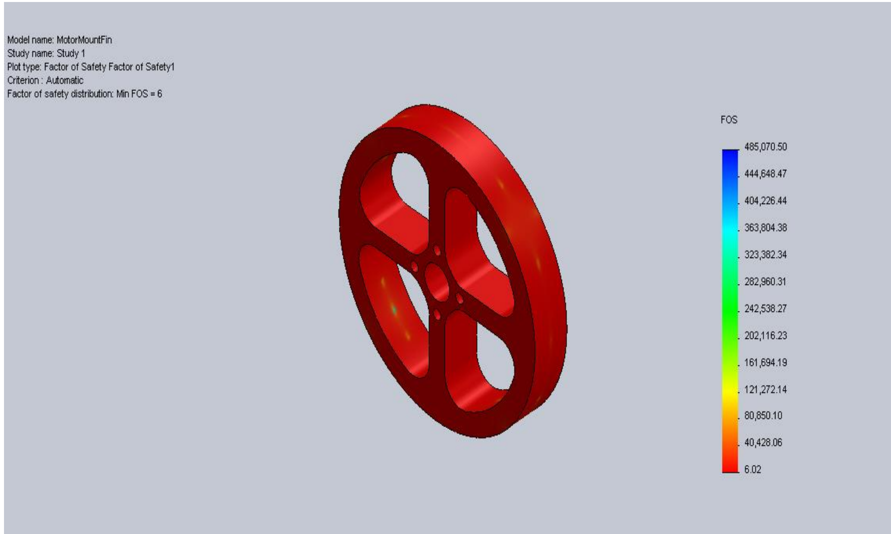

Figure 10: Motor Mount Safety Factor

5.7 Further Analysis Plans:

Beyond the theoretical testing of the ROV physical testing will be implemented. These tests will account for speed horizontally and vertically. In addition to these tests progressive depth testing will be implemented with the first test being to simply test the ROV in an assembled state with no electronic components to verify that there are no leaks in the pressure vessels. Once the ROV is tested and physically verified that no leaks exist the remainder of assembly will be conducted then performance testing and trimming the buoyancy will occur and extend beyond the time frame of this design project to prepare for competition.

6 Prototype Construction:

6.1 Overview:

With analysis leading to better definitions of the design requirements and a preliminary design developed construction is capable of beginning. Materials were researched and selected through the analysis portion of the project. It was determined to implement primarily aluminum, acrylic and PVC for a majority of the components to help reduce oxidation on the ROV and help extend its life potential. Because of analysis supporting the preliminary design and not indicating potential concerns the preliminary design was selected for construction with minimal changes to better accommodate manufacturing.

6.2 Specifications and Industry Standards:

Through construction of the ROV it was found that no significant information could be found regarding standards for integrity and requirements. Based on the MATE ROV Safety Guidelines the ROV is classifiable as safe with the propellers being fully shrouded, wired being secure and sealed from water. Because of this specifications for standard fasteners were implemented using ANSI fasteners that met standards set through SAE J429 and ASME B18.2.1 standards. The pressure vessels are composed of plastic and do not sustain enough pressure to have industry standards outlined so implicit standards were set by attaining material properties based on ASTM guidelines for the materials and analyzed based on theoretical calculations and implementing mandatory minimums of 1.2 for a factor of safety since human life is not directly a factor with the operation of the ROV in water, which accounts for an application of areas with minimal human interaction. Due to the construction requiring through holes for bolts, a 10% oversize was implemented on all through holes to allow the bolts to freely pass through their fixtures. In addition to this the declaration of specifications with brushless dc motors does not fit a standard convention and the kV rating for these motors must be translated to typical conventions to perform the required thrust calculations.

Typical RC servos are not intended to be operated underwater, however the Hi-Tec 5086WP servo falls in the micro class which is required for the gripper assembly and meets IP67 standard, which made it a candidate for the ROV. The IP67 Rating is based by International Protection Ratings and defines this servo as being dust sealed and waterproof up to 1m. Due to the fact that the servo is not a critical component and currently the best suited off the shelf component it was determined to proceed with using it on the ROV.

Additional considerations were made for the metal components implemented in the ROV regarding ease of replacement and their compositions and their ability to be used in a saltwater environment. This eliminated most steels from being able to be used as cross members, but due to the simplicity of replacing basic bolts was left as a viable option due to the significantly lower cost and the fact that with detailed service the fasteners will be removed to allow inspection or replacement and upon adjusting buoyancy for different densities of water many of the bolts may be removed and replaced. For the cross members Aluminum 6061 was used due to its weight, strength, ease of machinability and corrosion resistance.

6.3 Description of ROV Prototype:

The structure for the ROV is acrylic sides with aluminum connecting rods. In addition to these components the motors and props will be housed in PVC pipes to reduce the chances of debris damaging the drivetrain and allow for various mounting points the thrusters. The pressure vessels are planned to be clear PVC with caps to allow for easier manufacturing, monitoring for flooding and to serve as a lens for the camera that will provide operator feedback.

6.4 Parts Requirements:

Table 3 shows component prices based on quantities needed. The column with projected prices lists prices that are currently defined by required specifications and items with an asterisk are components that have not been completely defined at initial estimation of cost. Actual price variances are based on what components were actually purchased for the prototype, variances from projected prices that were defined within specifications are due to finding a lower priced source or from having a beneficial additional feature or more convenient way of attaining those products. Because of accessibility and adding more potential with certain components the PVC cost was slightly higher due to sourcing from a local hardware store, motor and ESC expenses were higher due to using a higher amp ESC to essentially provide the ROV with more horsepower and the endcaps were custom made to help with aesthetics and minimizing drag from potentially bulky caps that can be obtained off the shelf.

Table 3: Component Cost

Item	Quantity	Projected Price	Actual Price
Brushless Motors	4	90	39
ESCs	4	Included With Motors	100
Propellers	4	100	46
Arduino Mega/Sensor Shield	1	30	21
Webcam	1	40*	15
Sensors/Lights	1	20	20
Gripper Assembly	1	12	12
Voltage Regulators	2	40*	0
Servo Motor	1	20	20
Composite Sheet (2 feet x 1 foot)	2	100*	27
Aluminum Rods (1/2 inch x 1 foot)	6	12*	12
Cat5/Power (100-200ft)	1	85	80
PVC 3 inch	4ft	10	12
Clear 3 inch SCH40 PVC	2ft	37	22
PVC caps	2	5*	100
Waterproof Connectors	2	50*	0
Total		651	$531
*= Estimated cost not priced per specification requirements			

Many of the components were attainable through Hobby King which served as a resource for attaining the Electronic Speed Controllers, and the waterproof servo for the gripper assembly. In addition to this many of the basic components such as the propellers, Acrylic and other electronics were found on EBAY. The final primary component used is the gripper assembly which was found through spark fun. Aside from the gripper assembly these components were previously analyzed and found to meet the desired specifications required from this project. All additional hardware for assembly was all sourced through a local hardware store.

6.5 Manufacturing:

With insight from Mr. Zicarelli it was discussed moving some of the component mounting holes to help ease the manufacturing requirements. Based on his recommendations so components can more easily be attached for manufacturing within his CNC manufacturing holes were added to the motor mounts which made a minimal decline in the safety factor however it remained significantly higher than required. In addition to this the frame pieces had their connecting rod bolt holes shifted to allow a smaller footprint for the table within the CNC located in the Manufacturing lab. Other manufactures were contacted to compare pricing with costs near double and no feedback for recommendations to reduce cost was provided. This aspect of the project was difficult due to the fact that various manufacturers do not outline all of their amenities in regards to various dimensions that can cause special manufacturing fixtures to be required thus potentially causing an unintentional increase in cost. During the design phase heavy focus was made to make all of the tool radii to be at least ¼ inch to increase tool accessibility. Hardware selection was made based on easy to find but acceptable components and the linking rods were manufactured by simply cutting the aluminum, facing the ends to keep a relatively uniform tolerance and the lathe was also used for drilling and starting the tap to cut the required threads.

Due to the high cost of material to produce the endcaps for the electronics tubes it was determined that 3D printing was a possibly feasible option. Various quotes were sought out with the cheapest being Ryan Lucia who charged one hundred dollars to print all four end caps. These caps were printed with 80% fill utilizing ABS plastic and cleaned to allow smooth surfaces for mounting the O-Rings to establish a secure fit.

6.6 Construction:

The manufacturing of the ROV has been conducted at FIU with assistance of equipment in the manufacturing lab. As Figure 14 (Appendix) shows our components are primarily connected through an Arduino UNO which allows for multiple channels of component interfacing which will allow for easily being able to add more features to the ROV depending on the applications it will be facing. Through development of the ROV it was decided to implement an Arduino UNO to minimize space being utilized within the electronics housing. This change was evaluated and decided to be made due to the abundance of channels the UNO has for this project and because the Mega would be significantly more channels then what would be needed and this decision would reduce cost slightly. In future applications of the ROV the microcontroller could easily be changed due to the modular components selected and on an as needed basis for the hardware configuration desired.

Changes that were altered from the preliminary concept would consist of the use of an amplified USB cable, rather than Ethernet to simplify the serial communication to the Arduino. By implementing an amplified USB cable the maximum distance the ROV can operate is reduced to 65 feet rather than 200 feet that Ethernet at standard specifications for local connections can safely provide. Due to this change there is no difference in cost, but programming becomes expedited and a direct connection to the Arduino is established to allow easier accessibility for programming modifications.

Initially the tether was desired to be removable but due to resources for attaining waterproof connections for power and communications it was found to be quite expensive. This caused the team to decide on a permanent tether for the prototype which will eliminate the expensive waterproof connectors and minimize additional potential failure points.

At this point a full mock construction of the ROV was made to discover any minor fitment issues that may need made and the ROV was built. A setback the team had is when installing the End caps the O-Rings that were ordered had an outer diameter that ended up being too large for the inside of the clear PVC and the O-Rings needed reordered in a smaller dimension. Upon realizing this it was decided to mount the endcaps in a lathe and turn them using a 1/8 inch grooving tool to cut a deeper channel for the O-rings which solved the problem of the channels essentially pushing the O-rings too far out and causing a hard clash in dimensions. In addition to this the protective covering for the electronics tubes was removed since handling was going to be minimized as the frame would be in place to provide some added protection. It was noticed that the clarity of the clear PVC was less than anticipated as seen in Figure 11. To try reducing some of the weight and increasing buoyancy a thin wall PVC was utilized. This caused the outer diameter of the PVC to be 3.25 inch rather than the planned 3.5 inch as seen in Figure 12. This change was to cause a reduction in the weight, increase the buoyancy and additionally reduce cost. Due to this change the plans for the original chassis caused the thruster ducts to have an extra .5 inch horizontal distance, which can be seen in Figure 13. Due to the more narrow profile of the duct assembly the ROV was able to be narrowed further decreasing drag of the overall system making the available thrust more effective.

Figure 11: Assembled ROV Chassis

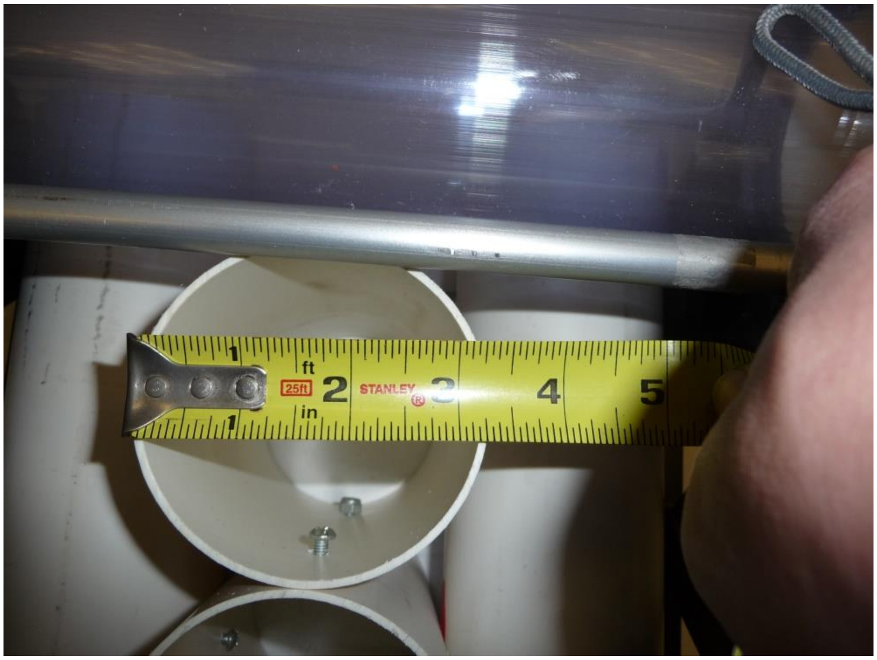

Figure 12: Thin wall PVC Duct

Figure 13: Extra space between frame and ducts

6.7 Installing Motors:

With assembly under way many more design decisions can be made as components are finalized. The vertical thrusters were mounted to the motor mounts and placed within the ducts to determine the potential arrangements for the propellers. One way of mounting the motors was with the propellers facing downward, they would more easily be fully engaged within the body of water which would decrease the potential of cavitation, at the surface, that can occur from the propellers having more thrust then the applied pressure of water. By mounting the motors with the propellers facing upward it was noted that the propellers would be less effective in use at the surface but by having the mount at the bottom where sediment and potential debris from operating near the ocean floor, would be more likely to enter the duct allowing the mount to potentially stop debris to reduce some potential propeller fouling. In addition to this, gravity will cause the propeller fall downward with shaft failures which the motor mount will also be capable of catching it in a failure allowing reuse of one of the more expensive components which makes the upward mounting more lucrative. By positioning the motor as low in the duct as possible it allows for the ROV's buoyancy and mass correlation to force the ROV upright since the primary locations of mass would be along the lower region of the ROV. Installation was conducted by drilling and tapping the ducts and motor mounts with 8-32 set screws and screwing the mounts and ducts together. Based on observations made in the preliminary testing of the ROV the horizontal motors had their mounting locations noted and the horizontal thrusters were then mounted.

To assist in cable management for the motors power cables the motors were turned to aim the wire leads towards the centerline of the ROV to follow a path with as direct of a wire routing as possible. This allowed features of the ROV to be utilized for managing the wiring such as the small gap between the vertical thrusters and the horizontal thrusters, and the small gap between the aluminum cross member and the electronics housing. Holes were then drilled behind the motor mounts and wires were fished from the motor out of the duct and to their connecting point. This allowed minimal wiring within the duct to reduce the possibilities of sucking the wiring into the propeller and causing a catastrophic failure.

6.8 Cost Analysis:

Based on an average labor rate of approximately $30 per hour, an average wage for lower level engineers, for each member of our team as seen in the table below the prototype development cost is currently at approximately $3630. This cost if the design would move to a higher production volume would however be broken down through the sale of each unit as much of this expense is accumulated through prototype development and baseline testing. The materials costs are still being calculated as research is conducted to help determine the final items in the design. Currently full prototype development cost including labor is at $4375 for a single prototype unit, which would account for paying for design, all manufacturing and consumer based pricing for all components. Due to manufacturing requiring CNC milling procedures prototype costs will also account for programming and an initial setup that will be capable of being shifted throughout potential production units if this design were to become actively manufactured. These aspects along with being able to purchase in higher volumes will offset costs in an actual production scenario that can be approximated upon completion to help validate that this design will be a likely candidate for a small modular ROV that may be highly lucrative for various industries to invest.

If this project were launched to production, revenue from unit sales would offset the development costs of the prototype. This is based on additional research not being needed beyond prototype development and essentially causing expenses for additional units to be manufacturing, and material expense. To determine a projected retail price for this concept a 10% reduction in material costs due to bulk pricing and manufacturing being able to go to typical lower skilled labor rates of $15 per hour can be assumed making each unit approximately $765. To recover expenses and keep a lucrative pricing the ROV can be sold as a complete product at a price similar to the OpenROV product in kit form. If typical price markup of 10% occurs on this product a retail price would be set at approximately $850 which will have a capital recovery occurring at 37 units being sold. Based on Kickstarter's numbers for donations to the OpenROV project 79 donors contributed $775 for the preliminary sales of the kit for of the OpenROV and 19 contributed $1200 for preassembled kits which shows that our breakeven point should be easily attainable. Pricing would have to be assessed based on how beneficial the power and mobility this particular ROV has in comparison to what is provided with the OpenROV since it is the most comparable and from a company without significant history for value added by a reputable company backing this particular product. In comparing this product with the fully assembled OpenROV unit with a price of $1450 this ROV can potentially have a markup ranging to 90% and capital recovery occurring with production of only 5 units.

By comparing the light commercial grade ROV's with our ROV it is apparent that mobility and depth factors are driving costs in ROV technologies. Currently one of the lower cost commercial grade ROV's the VideoRay Scout costs approximately $5000. This particular system is much more similar to the ROV that our team designed with primary differences being a clearly defined depth rather than a theoretical depth, brushed motors with proven reliability compared to the brushless motors that our ROV implements and a known reputation for quality products being released by VideoRay. By being able to offer a price at nearly 1/4 the cost of current "economical" solutions this project has potential to being a great success as a business model and as a driving factor in technologies and design methodologies affiliated with the ROV industry. There are some minor issues that will be discussed and addressed in the future that will increase development costs but with the project at its current state many of the expenses are accurately accounted for which will keep cost near current figures.

6.9 Discussion:

Through checking with many of the standards it shows that the field this project is part of is relatively new. Based on assessments of the design with considerations for manufacturing it is easily attainable and should be ready for full manufacturing with minimal changes. To help add to the sustainability of the design further research of components must be made and a full cost benefit analysis must be performed to better determine what options are viable. Because of manufacturing insight provided by Mr. Zicarelli the design was modified minimally to account for manufacturing on a CNC mill with a slightly smaller work table and manufacturing holes were added to the motor mounts. These oversights in design allowed being able to reduce cost and help make the ROV more achievable in a manufacturing setting. Because of many of the components being accounted for through utilizing relatively accurate abstract specifications minimal unexpected expenses are likely to arise. Additionally by keeping a simple approach to much of the construction requirements and utilizing simple relatively common components the cost analysis of the project shows that it has potential to thrive in market.

7 Design Considerations:

7.1 Assembly and Disassembly:

Assembly of the ROV consists of bolting the aluminum connecting rods between the frame plates. Once one frame plate is bolted to the structure the electronics tubes and thruster ducts can be installed paying attention to wire routing to minimize the potentials of wires being able to enter the thruster ducts. This is done by utilizing SAE ¼-20 bolts with a minimum ¾ inch length to allow for ¼ inch of thread engagement. Longer bolts can be implemented for adding and distributing counter weight to adjust trim and buoyancy properties or for additional hardware. Upon implementing the gripper it must be noted that the ½ inch aluminum connecting rods in the front of the ROV must be the rods with additional holes tapped in their centers. After the ROV is bolted together final assembly can occur with wiring signal wires from the ESC's and any additional hardware to the Arduino as outlined in the user manual. At this point silicone grease can be applied to the O-rings and this cap may be installed. Now the second cap may be installed which requires connecting the positive and negative cables from the tether's cap to the cables in attached to the ESCs and the USB must be connected to the Arduino, note the connections may only be made in one possible orientation and the color red is also in place on the connections to identify the positive power cables. Upon establishing the power connection the Arduino's USB connection can be made and the wires may be fed into the duct. Prior to pressing the tether's endcap into the tube silicone grease is to be applied to the O-rings and the cap may be pressed on slowly to allow air to bleed from the tube. The final endcaps on the cameras housing are also ready to have the O-rings greased and pressed on to seal the forward electrical compartment. At this point waterproofing may be checked by submerging the sub for a period of time, retrieving and inspecting to see if any water has entered the electrical tubes. If the waterproofing integrity of the ducts is intact the ROV's USB cable may be connected to the laptop, the user control interface can be connected and power may be sent to the ROV. Once these connections are established the MATLAB based program may be ran and operation of the ROV may begin upon completion of the arming sequence.

After operation of the ROV it must be rinsed with freshwater to clear potential oxidizing deposits and lubricant should be applied to all metallic surfaces to inhibit oxidation. Disassembly of the ROV can occur from full disassembly which is simply reversing the assembly order or by simply prying the endcaps loose very slowly to prevent breaking the plastic. Upon removal of the endcaps the components may be removed and serviced or replaced.

7.2 Maintenance:

This system has minimal maintenance aside from a freshwater rinse of the system and lubricating the metallic surfaces to inhibit oxidation. For detailed maintenance the propellers can easily be removed by chocking the motors and loosening the center hub bolt of the propellers. Propellers can be inspected for fouling that may occur over time and replaced on an as needed basis.

Major maintenance must be conducted in a safe manner due to the electrical components that can be a catastrophic loss. Primarily waterproofing failure is the most critical concern of the ROV system. Upon discovering a potential leak connections to the ROV should immediately disconnected to minimize electrical failures and the electronics tubes must be checked for moisture. To determine where a leak may be originating paper may be packed in each end of the electronics tubes and the unit may be submerged and inspected to see which side may be the source of the leak. Upon detection careful inspection of the O-rings must occur with replacement and re-lubrication if necessary. If it is discovered that the leak is occurring through the wiring not being adequately sealed Rust-Oleum Leak Stop may be applied to that cap and wires to reform a barrier. If motor failure occurs the motors can be unbolted, de-soldered after carefully cutting the heat-shrink and sealant and replaced with a similar 1000kV brushless DC motor. Upon ESC failure the faulty ESC must be removed from the electronics duct, the wires from the ESC must be cut and a replacement 45 amp reversible ESC must be soldered into place. Replacement of the Arduino can simply be conducted by unplugging the Arduino and making the appropriate connections to the replacement.

7.3 Safety:

Due to the high speeds of the propellers within the duct, caution near this area must be exercised. To convey the general caution warning it was decided to paint them a color that has common affiliations with hazardous areas. This was decided over simply labeling the area due to the fact this system is in motion so reading a warning may not always be a possibility. These typical hazard colors would consist of red, orange and yellow. Within water certain frequencies become dampened as depth is increased. Research was conducted to discover which color would be best to implement with the most effective visible range. Because of color losses within the depths of water as seen in Figure 14 and common colors for alerting people to potential hazards yellow was decided to be applied to the duct assemblies since it is visible from the greatest depth.

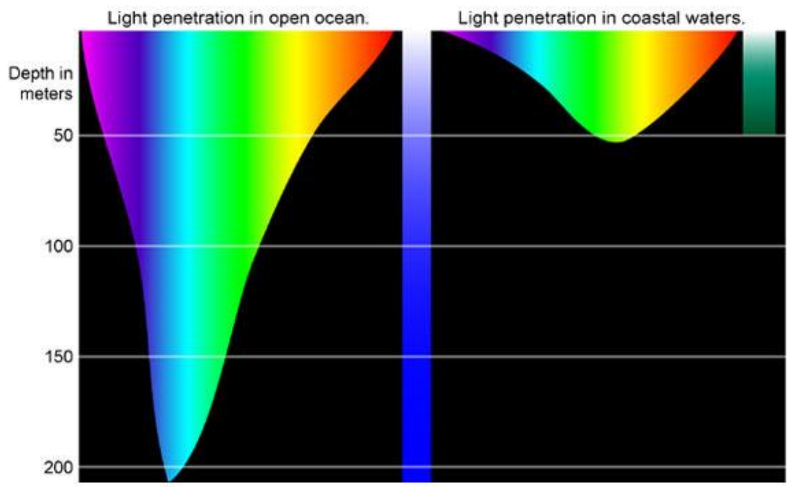

Figure 14: Color Penetration by Depth [14]

In addition to simply providing a visual reference towards a potential danger other efforts were made to mistake-proof the design. By routing the wiring through more permanent structures the wiring of the ROV will be less likely to become loose and become a hazard. These efforts include wiring efforts with labeling the ESC's harnesses to ease making connections to the Arduino. Beyond this efforts were made to enable full disassembly of the ROV for adding to serviceability.

7.4 Environmental Impacts:

Environmentally the ROV can be utilized to monitor waste retention ponds, explore areas that are prone to litter for cleaning, monitoring reef habitats and studying various aquaculture and structures through its operational regions. Additional accessories can be added to the ROV for more industrial applications such as sonar, thermocouples, light sensors, pressure sensors, and other tools that can aid in researching underwater environments for their aquatic sustainability. The environmental impact that the device has after its life cycle is that all of the electrical components can be repurposed for use in other remote control, robotic or research projects. The frame components of the ROV are all recyclable which will allow minimal waste after processing is complete.

7.5 Control Software

Initially, research was done into the various functions and methods available in the MATLAB Arduino package. It is important to note that in order to interface the electronic speed controllers with a microcontroller, servo signals could be used to control the speed and direction of the attached motor. Fortunately, MATLAB provided a convenient means to assign servos to specific microcontroller pins and then send servo signals to those pins. In this way, code could be written in MATLAB to control each thruster individually. With this knowledge, coding of the control software could begin.

Initial development and testing of the control system occurred at very early stages, taking place before the chassis manufacturing was complete. This allowed for work to be done in parallel in both manufacturing of the ROV and coding of its control system. At first, the means to utilize the electronic speed controllers was implemented and tested. One thruster assembly, consisting of an ESC and a brushless dc motor, was connected to the microcontroller on pin 2 and power was supplied via a 12 volt Lithium Polymer Battery.

It was discovered that the ESC would not simply respond to the servo commands as anticipated. Research showed that the ESC would need to be armed by a specific sequence of throttle values. This arming sequence was sourced from the specification sheet for the device which would allow for the control software to arm all ESCs when first initialized. The arming sequence code is shown in Figure 15.

```

%Arming ESCs
fprintf('Arming ESCs... ')

ROV.servoWrite(LEFT,0);
ROV.servoWrite(RIGHT,0);
ROV.servoWrite(FWD,0);
ROV.servoWrite(BACK,0);

pause(1.5);

ROV.servoWrite(LEFT,180);
ROV.servoWrite(RIGHT,180);
ROV.servoWrite(FWD,180);
ROV.servoWrite(BACK,180);

pause(1.5);

ROV.servoWrite(LEFT,90);
ROV.servoWrite(RIGHT,90);
ROV.servoWrite(FWD,90);
ROV.servoWrite(BACK,90);

pause(1.5);

disp(' Armed!');
```

Figure 15 ESC Arming Sequence

After determining this arming pattern, it was decided to best begin with a simple control scheme and then build from there. For this reason, we began coding a simple keyboard entry style control system in MATLAB. Upon execution, MATLAB would establish connection with the microcontroller. Pins two through five would be assigned as servo pins for the attached ESCs and pin six for the gripper servo. The control software would cycle the gripper open and shut, then place it in the mid position. The ESCs would then be armed by writing a specific series of servo angle values corresponding to maximum throttle followed by minimum throttle and, finally, neutral throttle as discussed earlier. Figure 16 shows the start-up of the control program. MATLAB would then wait for keyboard input to determine the next action, with specific keys corresponding to specific ROV commands. The number pad was chosen for motion commands, the number 8 key being selected for forward motion. Once a command was entered, the ROV would, for example, energize the corresponding thrusters to create forward motion until the command to halt was received. This step control scheme functioned but was not very user friendly and further development was needed.

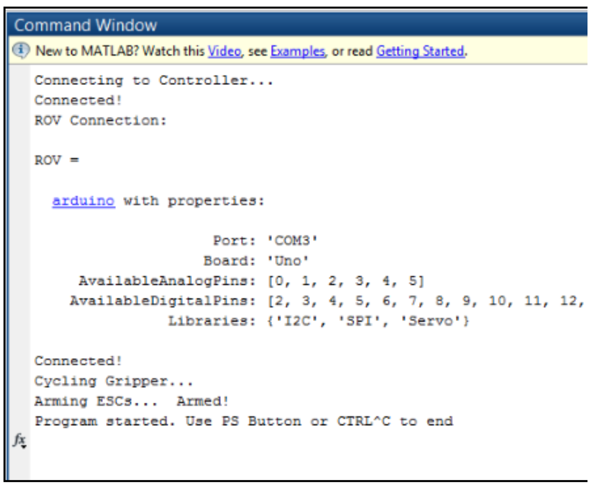

Figure 166 Control Program Start Up in MATLAB

Figure 17 Dual Joystick Controller

In order to make the system more responsive, it was determined that a joystick needed to be integrated. Fortunately, MATLAB includes functions to read joystick axis positions as well as button status. Using this method, we were able to create a control scheme that periodically queries the axis positions of a joystick and button press statuses of an attached game controller, shown in FIGURE 17. Then, depending on these values, the corresponding branch of code would be executed, thereby producing the desired ROV action. This created a much more intuitive and responsive system. Additionally, an increasing throttle scheme was implemented such that initially motion commands would start with a reduced throttle value and ramp up as motion was continued in the same direction. This allowed for both fine movement control as well as quick motion for travelling longer distances. Additionally, the code is written such that any specifications, like maximum thrust for example, can be modified simply by changing one value. This would allow for easy modification and fine-tuning in the future.

Due to the addition of i2c functionality implemented in a newer version of MATLAB, specifically 2014a, further work was then done to update the control program code to make use of this feature. This required an overhaul of all the control code that employed servo methods as they were completely altered in the newest MATLAB version. Additionally, an analog thrust feature was implemented. This takes advantage of the joystick's analog input and allows the user fine control of the speed of the ROV. Finally, a temperature sensor was implemented to allow the monitoring of internal compartment temperature, necessary due to the amount of heat that the ESCs produce during operation. Thus far, the control software has undergone six distinct iterations, each improving upon the last, and is still undergoing development. Appendix C contains the current version of the control code implemented in MATLAB.

8 Testing and Evaluation

8.1 Overview:

Beyond just simply developing a design and providing analysis that can show how likely it is to succeed, testing must be conducted to validate how effective the whole concept actually is. This is due to losses and changes that are not easily accounted for which are friction, efficiency of the propeller design, power inconsistencies, different densities in water, drag from the tether, and unexpected errors in manufacturing. By conducting tests in a certain progression it will minimize the potential of a catastrophic failure, increase the effectiveness of the final concepts design and help demonstrate the capabilities of this particular ROV to show how well they correlate with the design objectives.

8.2 Planned Testing:

Testing for the ROV will consist of testing individual components for function within limits that will be established based on analysis and keeping conservative values to help safeguard the design from failure. This will reduce the chances of a catastrophic failure that will cause significant financial loss of the team. In addition to these tests trials will be conducted in a pool to make adjustments to the ROV configuration and tune its performance potential. Finally testing regarding the velocity of the ROV and capabilities of the thruster configuration with regards to mobility and the effectiveness of the control system will be assessed.

8.3 Preliminary Testing:

In this test the ROV chassis was in a near fully assembled state with all of the key components in their designated areas of the ROV and it was placed in a body of water as seen in Figure 18. The horizontal thrusters were not mounted which allowed for sliding them towards the forward or aft section of the ROV and the vertical thrusters were mounted in their final location. By being able to move the horizontal thrusters the best location can be found to mount them in a manner to establish a more natural weight distribution for trim across the entire ROV. During this test a few key components of the ROV's construction were examined.

Primarily a concern of the ROV was waterproofing of the pressure vessels. Since no power was supplied to the ROV it decreased the risk of shorting the ROV and would only result in some potential swelling of chipsets and mineral deposits on contact surfaces making it a low risk test. If waterproofing was to be examined during testing with power shorting could occur and lead to a catastrophic failure that could cause a loss of key electrical components.

Figure 17: ROV in near full assembly in water

The waterproofing of the pressure vessels with the design of the double O-ring caps proved to be a partial success. There was a failure within one of the caps where water was leaking through the layers that compose the 3-D printed structure of the end cap. Further research is needed to determine a treatment processes either by coating or heating that may help bond the layers and create a better barrier to seal the components.

Based on the angle the ROV was sitting in the water it became obvious that the horizontal thrusters needed shifted further forward. After shifting them fully forward the ROV was sitting nearly flat within the water as seen in Figure 18. By having the ROV nearly flat for its natural orientation minimal trimming of weight will be needed for different accessories that are attached to the ROV. After determining this mounting location it must be noted that the ROV is still sitting with the forward section pitched minimally upward, however once wiring is ran it will not be contained in just the rear electronics tube and should flatten the profile the ROV is sitting. The difference in mass from the gripper and all of the electrical components is only .5 pounds and the moment arms are similar distances, which makes minimal changes in component configuration more drastic in adjusting trim.

Based on the final assembly of the ROV the net positive buoyancy force is approximately .5 pounds, this will allow the user to weight the ROV and trim for neutral buoyancy remain more constant in depth rather than having to add positive buoyancy. Adding positive buoyancy will result in needing to add foam or air bags that would produce significantly more drag, so it is essentially a good characteristic to be positively buoyant since adding more mass would be less detrimental to minimizing drag than adding lift. By having positive buoyancy with the ROV in this state it also allows the end user to rig it using hardware that will make it closer to neutral or slightly negative. Since this unit is a prototype with no extensive history to validate reliability the team will work through testing to trim the ROV to attain a closer to neutral profile but as a whole is currently still wishing to retain a slightly positive magnitude to force the ROV to the surface upon catastrophic failure during testing.

8.4 Software Testing:

Testing of the control code was performed along the entire development process. As mentioned before, some testing was required when initially attempting to send commands to the ESCs for each motor. Not previously mentioned, an additional problem was encountered during testing. When changing the spin of the motor from full forward to full reverse, the motor would stop and the corresponding ESC would stop functioning, no longer accepting commands. This bug was corrected by implementing code to briefly send the stop signal to the motors between direction changes. This nearly imperceptible pause in motion served to eliminate the error.

Additionally, after any new implementation or improvement of an aspect of the control system, testing was performed to verify that changes implemented in the code produced the desired effect. For example, after adding the ESC control code, gripper control was added. Several tests were made to ensure that the gripper behaved as desired. The initial implementation involved a control loop where the position of the gripper servo was queried and then subsequently incremented and written as a new servo position, allowing the gripper to open or close. During testing, a large bug was discovered when the gripper was repositioned while fully open or closed. Writing a servo value smaller than 0 or larger than 180 degrees resulted in a fatal error that caused the code to crash entirely. This was corrected in the code by implementing hard maximum and minimum value limits on the written servo positions.

Additionally, as manufacturing and wiring of the ROV neared completion, more testing of the control code was done. Once the motors were mounted and ESCs were hardwired, testing had to be performed to ensure that the motors rotated in the correct direction, producing the desired thrust orientation. During testing, we discovered that one of the horizontal thrusters spun in opposition to the desired direction. This was quickly corrected and documented in the control code. Additionally, as initially coded, the vertical thrusters produced thrust in the wrong direction for ascent and descent. This was also corrected and documented in the code.

8.5 Secondary Structure Testing:

After the electrical components were tested, the basic constraints were acquired to develop programming to operate the ROV and the pressure vessels were diagnosed for only one endcap leaking additional testing was needed and final assembly had to be performed. The leaking endcap needed sealed and certain endcaps needed drilled to allow wires to pass through and they needed resealed. To seal the one leaking endcap epoxy was coated through the inside to provide a solid barrier and help fuse the printed layers. Once holes were drilled that were just large enough to pass the required wires to the outside of the electrical compartment sealing needed to occur so a marine grade adhesive was applied to seal the passage of the wiring through the endcaps. Since it was known that the ROV was approximately .5 pounds positively buoyant washers were bolted to the lower frame mounts to help converge to a neutrally buoyant state.

The ROV was once again submerged and left at the bottom of a pool to check for waterproofing integrity. After about 15 minutes the ROV was retrieved and inspected for leaking. Leaking was once again discovered with approximately 1 ounce of water being found in each compartment which due to initial waterproof testing was determined to be from the wiring passing through the endcaps. All of the electrical components needed thoroughly dried and brainstorming occurred to find a better way to help waterproof the connections. Due to the amount of water discovered in the pressure vessels it was known that the leaking was minimal and it was also noted that pressure generated by pressing the caps into the tubes was high enough to push the endcaps off and the caps needed held in place to allow air to slowly bleed out of the pressure vessels to allow them to fully seat.

Based on the observations noted in this series of tests it was known that the ROV is very much near an operable state with minor adjustments needed to make it fully waterproofed. Due to removing excess wire from the ESC's to the motors it was known that less mass would be onboard and slightly more weight was needed then the ½ pound determined in the previous test. Additionally in this test buoyancy properties were checked with approximately ¾ pounds of weight added to the ROV. It was discovered that the ROV sinks very slowly in a uniform manner. Because of its sinking being uniform the mass distribution is acceptable and the ROV will operate in an effectively trimmed manner. This will allow for the profile of the ROV to be in the anticipated orientation and the fluid flow properties to be near ideal with the analysis that was conducted in the development of the design. Because of the ROV being slightly negative however it will constantly want to sink which will take away from the neutrally suspended state that is desired so mass will need to be removed uniformly around the ROV.

Upon completion of the secondary structure testing all of the electronics housings were thoroughly dried and components were dried. Rust-oleum Leak Stop was applied generously to the endcaps to help seal the areas around the wires to help stop water from entering the electronics housings. In addition to the Leak Stop, Never-Wet was applied in multiple coatings to the onboard electronics. Never-Wet was determined to be a viable addition to the system due to being a hydrophobic spray that is safe for electronics. Because of applying the Never-Wet in the event of a breach in the electronics housing operation of the ROV can resume and actions can be taken to surface the ROV since it essentially forms a barrier to repel water from the electronics.

8.6 Final Testing:

Having fully waterproofed the ROV, operational testing could begin. Once connected and initialized, the ROV was submerged in the pool for evaluation. Initially, general maneuverability and control were tested. During testing the ROV responded, for the most part, as expected. The implemented control system made it fairly easy to control the vehicle and maneuver throughout the evaluation. However some minor issues were noted during these tests.

In maneuvering the ROV, it was noted that a slight drift was prevalent. When driving the vehicle forward it would consistently pull slightly to the right. This would require the operator to stop the vehicle and readjust had it veered too far off-course, making it difficult to maneuver long distances efficiently. This slight drift may have been caused by one, or more, factors. Slight inconsistencies in motor output or positioning of the horizontal thrusters may have caused this veer. Additionally, the manner in which the motors were connected required different servo values for each motor in the control code in order to turn in the same direction. This issue may have caused some variance in the motor outputs for the horizontal thrusters and, thus, contributed to the slight drift.

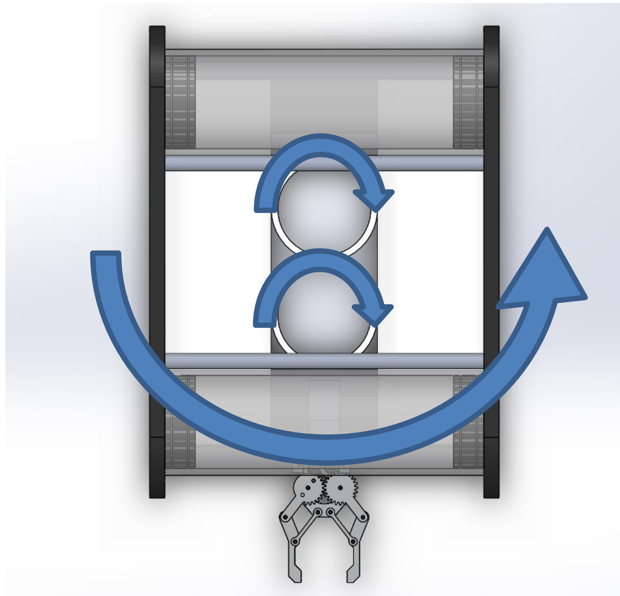

Figure 18: Rotational Moment Generated By Thrusters

Additionally, a significant issue arose during ascending and descending maneuvers. It was observed that during ascent, the ROV would rotate significantly about the y-axis. This motion was unintended and added difficulty in controlling the ROV effectively. It was determined that this was caused by rotation of both vertical thrusters in the same direction. This results in a torque and, therefore, a rotational moment on the vehicle as shown in Figure 19.

The ROV was then tested for maximum velocity. It was determined that it could safely operate at approximately 1.5 meters per second or 3.4 miles per hour. This top speed was hindered due to the operator having to constantly counter maneuver the slight veer discussed above. It is suspected that the experimental velocity was significantly lower than our expected value due to two primary aspects. Primarily the torque provided by brushless motors was too small to provide the full RPM expected. Second with hobby based components propellers are often minimally defined causing many assumptions to be made in the selection process. With the hobby propellers the pitch and diameter are the main factors provided however other values can alter propeller performance such as cupping and slipping. Cupping essentially will add or decrease the effective grabbing potential of the propeller and slip is to account for frictional losses due to the leading edge sharpness and the surface finish of the propeller.

Once basic maneuvering was performed and proficiency began to increase, two objects were placed in the water for the ROV to be able to pick up. The operator made attempts at grabbing the objects underwater, as shown in FIGURE 20. With some added caution being implemented to the magnitude of control signals being sent the ROV, it was capable of reaching the objects, closing the gripper and bringing the sunken objects back to the surface for retrieval.

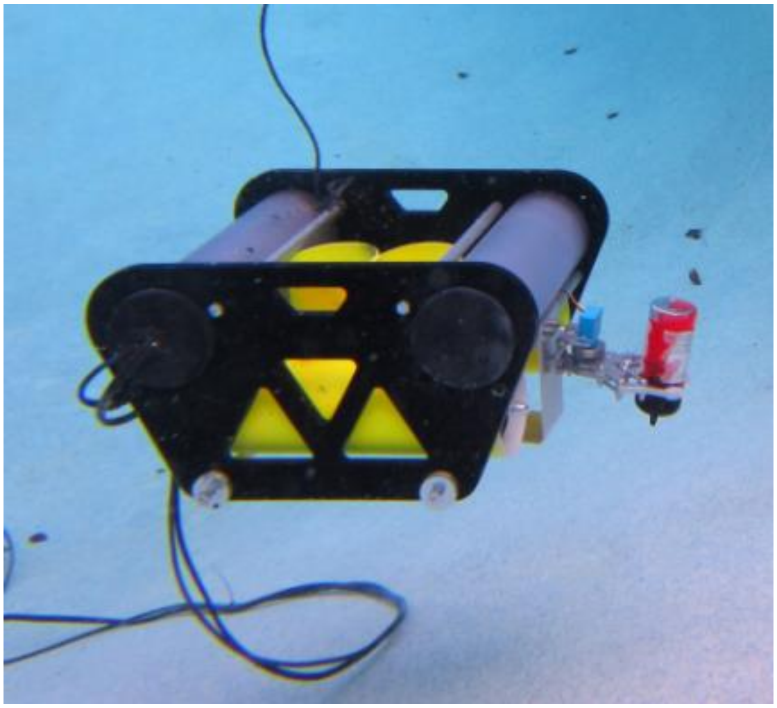

Figure 19: ROV Grabbing Container

8.7 Discussion:

Through the battery of tests performed on the ROV it was proven that the team successfully created a fully operable ROV with considerations to making the system as modular as possible. The testing proved to the team that their ROV is currently capable of about 1.5 meters per second or 3.4 miles per hour. This velocity does not meet the desired outcome from the team but is still a substantial speed for any underwater vessel at the scale and budget that produced this design. Through implementing a controller with a common configuration and coordinating the controls to relatively intuitive positioning the control of the ROV proved to be relatively intuitive with ease of operation within minutes of the first operating attempt. Because of this design being the first design attempt at developing an ROV by this team many minor issues were discovered through this testing that can be implemented in future improvements to this design or towards a future iteration of this design that this team or future teams that may approach a similar task.

9 Design Experience:

9.1 Overview:

This project required the students to account for many engineering requirements. Primarily kinematics was accounted for in developing the thruster configuration. Beyond this multiple aspects of fluid mechanics became critical factors. These factors include understanding the correlation of reactive drag forces with projected surface areas, buoyancy and the development of a pressure vessel. In addition to these considerations manufacturing capabilities were accounted for to help simplify the design and produce an economical solution. Finally an understanding of ergonomics and programming capabilities had to be expressed with the development of an intuitive control system that could translate an input to a desired output. Collectively these aspects all show being able to work within a broad spectrum of proficiencies to develop a fully functional prototype. This team had many learned experiences gained with trying to work in an effective team and sustain open communication towards one another when handing off work, conveying information and keeping other teammates informed with developments in the project.

9.2 Standards:

Through the development of the ROV many of the standards that were implemented proved to be successful. The gripper even though the application exceeds the outline for the standards had no malfunctions, more than likely this is due to implementing a higher design criteria to make sure this standard is consistently met in a production setting. Since much of this design is outside of the scope of typical Mechanical Engineering organizations many standards are essentially implicit standards that are constructed through analysis methodologies, with a given material property that is standardized by industry norms and a comparison of requirements vs potential established to provide a design factor that was selected as a mandatory minimum to insure success but have a reduced value since human interaction is minimal. Manufacturing standards that were established were based on standard ANSI 1/4 -20 bolts being used that will enable easy acquisition of hardware. With every bolt that was implemented as a through fastener a 10% oversize was accounted for to allow easy passing of the fastener yet a relatively rigid connection. Due to manufacturing capabilities and keeping a minimal cost, aluminum 6061 was kept as the cross member material to try keeping cost low since it is a relatively effective material. Upon completion of the design and checking the design with the MATE ROV Competition requirements and safety standards this design in its current form is completely compliant and capable of competing in the 2015 MATE International ROV Competition.

9.3 Professional and Ethical Responsibility:

As engineers it is our responsibility to develop means to achieve tasks that aid or improve life for people. Through development of this ROV it shows that the technology cost can be reduced substantially making it an attainable device by many people. This aspect will aid in the research that people can conduct by performing inspections of utility lines, bridges and other infrastructures that people have become dependent. Safety for the people and the environment in the operating ranges is also a paramount consideration. Because of this shrouds are going to be placed over the thrusters when operating in a less controlled atmosphere. By placing shrouds over the thrusters it will help reduce the likelihood of fingers being placed in the duct while propellers are spinning and it will help keep grasses, and fan corals from being consumed by the thrusters. These factors along with the use of materials that are all easily recyclable or easily repurposed allow the ROV to essentially produce no byproducts upon completion of its life.

9.4 Life-Long Learning:

Some critical components of this design that provided a lasting impact within the team included the benefit of being able to communicate ideas effectively. During primary concept development ideas were conceptualized that would be effective and potentially work, however team members challenged their attributes to try simplifying them more or simply dismiss them as being ineffective. At times the proposal of a preliminary concept and critique seemed to be attacking yet as the team would re-approach the drawing board each concept had attributes retained to collectively lead toward the development of the implemented system.

During manufacturing two vital changes were implemented. These were first creating holes that would be used to fasten the materials for the motor mounts and side plates. By creating these features it was observed that minimal changes in structural integrity resulted and the use of smaller and more common machines was capable helping reduce the cost. This aspect raised awareness of accounting for manufacturing equipment accessibility with creating a design to help ease the manufacturing processes that occur after design. Additionally with manufacturing it was determined that the endcaps should be 3D printed to reduce cost since typically it is a cheap prototyping alternative. By seeking quotes that would meet the requirements of this project it was found that 3D printing would be quite expensive but ease the burden of manufacturing more components within the team. At this point it was researched for materials cost to produce the endcaps by turning on a lathe and it was discovered to be nearly one quarter the cost of printing however time would be a factor since the team would become responsible for their construction. After finding a cheaper means to 3D print the endcaps cost became essentially the same and it was determined to save time, 3D printing the endcaps at a slightly lower quality then desired was a viable route. This proved to work for most of the endcaps however with the manufacturing technique small vacancies in the material caused the waterproofing integrity to suffer on one. This taught the team that even though certain processes are lucrative and may be viable in certain settings that sometimes it is a trade for overall quality with the product that may suffer and create difficulties later in production.

Upon completing the manufacturing of the ROV additional life-long skills were attained such as trying to consider the intuitive design of a control system. With the team having access to various controllers for gaming systems and interfaces for their computers it was determined to try reading signal from many of the devices and with what devices send for signals and assess their capability for an intuitive configuration since the controller can essentially be custom programmed for this application. Based on the configurations determined the operator was able to successfully gain control of the ROV within minutes and complete an objective.

9.5 Discussion:

Through the development of this prototype many considerations were implemented that collectively raised the team's awareness to the potential effects of our designs in the world. These considerations include the applications of our design, the safety of those operating the equipment and in the environment around the equipment and what happens with the product after it is rendered useless by either better technology, a lack of need or failures that may potentially occur. It also forced the team to think of how they can account for other users being able to operate the ROV and mind a budget and deadlines that are often included in working in the engineering industry. In addition to these aspects affiliated with the development of a product, lessons were learned that may help guide the team in future decisions relating to engineering with regards to their products they develop relating to the ease of manufacturing, the settings they may be operated, establishing redundancies for minimizing catastrophic failures and other critical decisions that may need made.

10 Conclusion:

10.1 Conclusion and Discussion:

Overall this project pushed the students involved to thinking of many aspects related to engineering to try devising a system capable of being implemented in industry and distributed through a potentially vast network of users. By accounting for a robust design and holding high expectations to design this system it allowed for the students to have various shortcomings that still allow the project to succeed in many other levels. Currently at the price of the ROV that was designed there is no system on the market with the potentials and a substantial markup is still possible. This markup however must be kept conservative due to the fact the project was initially an attempt to help drive the technology costs in this field lower. Because of the project successfully operating and the first user to be able to successfully and easily gain control of the ROV in the matter of minutes it is obvious that the controls are highly intuitive and many of the reactions of the ROV are anticipated which further make this design satisfying to the team involved.

Based on the previous years of the MATE ROV competition it is evident that based on videos seen from competition trials the team stands a great chance at performing well in the competition. By evaluating the design with its applications in the world the ROV can counter many of the oceans currents and a maximum operating depth is still to be accurately determined which indicates it is very likely for success in industrial applications.

Throughout the development of this design the ROV had minimal issues early on which made the project begin very rapidly, however at the end issues with the 3D endcaps and waterproofing integrity caused the team to re-evaluate some of the construction aspects. These issues gave the team the opportunity to troubleshoot and try devising systems that will benefit the overall design where earlier in the design process no issues had surfaced and minimal critical thinking needed implemented.

10.2 Evaluation of Integrated Global Design Aspects:

Based on the finished prototype several of the design attributes all correlate with a possible global application. The ROV is capable of being operated on a 12V DC power supply which can be sourced from any automobile, boat, or many pieces of heavy equipment. This allows for easy access to power for operation. Because of the size and weight of the ROV it is easily mobile by a single person and can be implemented in a number of possible environments. The design also allows for easy additions to the hardware to make it more applicable in various research potentials. Some shortcomings in the design are currently it is operated through MATLAB 2014, which limits the market due to the high cost of a fully licensed program even though student editions are only one hundred dollars. Additional development will be needed in devising other interfacing software suites to make this project more feasible to an end user. Overall the project is fully capable of crossing platforms to help reduce the financial expense of an operator suite. Additionally this design allows easy adjustments of the buoyancy which will also be a critical aspect when transferring the ROV from different temperature regions, and salinity contents, which will alter the waters density.

10.3 Commercialization Prospects of the Product:

Based on the cost analysis of the project it can be seen that comparable products all retail for a significantly higher cost then the development costs of the ROV. If accounting for developmental costs by setting a retail price on the ROV at near the cost of the current lowest price capital recovery can easily be attainable. In addition to the financial prospects of the ROV distribution is easily accountable as the required power supply is highly common and available virtually anywhere. Because of the Arduino microcontroller being open sourced support for a variety of potential additions can easily be discovered to expand the application ranges.

10.4 Future Work:

In future iterations of the ROV design many factors are being considered. The team is pursuing completing this project in its entirety with taking note to issues that may arise. Upon completion these changes will be noted with an effort to improve on the primary design to increase chances of success in competition and potentially market. Currently the desired design revisions include the possibility of changing the forward electronics compartment to account for clarity and minimize the potential distortion that may occur in its current form since the tube will result in a convex lens type effect with collected images. Additionally consideration is being made to future improvements of controls to try and enhance the potential of the thruster configuration that was selected. These changes to the project are being left for a later revision to help reduce the risk of exceeding the budget and time the team has established.

Additionally the 3D printed endcaps are likely to be replaced with the next design iteration. The double O-ring sealing system proved to be successful however the layers of the 3D printed surface allowed water to leak into the ROV and provided a relatively weak surface that works for a prototype but offers too little security for more rugged applications. With the revision of the endcaps going from 3D printed to machined, it will also serve as a great opportunity to try implementing waterproof connectors for the wiring to help establish a uniform surface to ease sealing the electronics housings.

When first outlining the goals for this project, many features were envisioned. Creating the control system in MATLAB helped to realize the main goal of having the ROV be easily modified, expanded, and improved upon. That said, many features were left on the cutting room floor as the time constraint and manpower available became an issue. Of these missing features, the most disappointing is the lack of a robust sensor assortment. Future work can be done to interface additional sensors to increase functionality of the ROV. Most notably, an accelerometer would allow for better control algorithms, PID control for example, resulting in significantly more stable operation. Additionally, waterproof sensors for data collection would expand the capabilities of the ROV outside the realm of the MATE competition.

Currently, the control interface is intuitive but lacking. The implementation of an analog joystick makes control of the ROV natural and easy, but unfortunately, the text based interface leaves much to be desired. The implementation of a Graphical User Interface (GUI) would greatly improve the operator experience. A GUI can make relayed data from the ROV easier to understand and utilize in operation, along with providing a more polished user experience. MATLAB offers tools to create such an interface but it may not be the best solution.

Finally, a limiting factor exists in the use of MATLAB in the control system of the ROV. Although easy to use and readily available to many students and industry members, it is expensive to purchase a license if one does not already have access. This limits the use of the control system in its current form. Future work may be done to port the existing control code to other programming languages, such as Python or C++. Although in order to do this, the features that were seamlessly added by MATLAB, such as joystick input and serial communication, would have to be coded or found in a pre-existing open-source platform. Overall, our choice in using an Arduino compatible microcontroller affords great flexibility in the future development of the control system, and current control software could be ported with relative ease.

References:

1) Moore, Steven W. *Underwater Robotics: Science, Design & Fabrication*. Monterey, CA: Marine Advanced Technology Education (MATE) Center, 2010. Print

2) Raymer, Daniel P. *Aircraft Design: A Conceptual Approach*. Washington, D.C.: American Institute of Aeronautics and Astronautics, 1989. Print.

3) "Application of a Remotely Operated Vehicle in Geologic Mapping of Monterey Bay, California,USA" *Diving for Science.* Pacific Grove, CA 1993.

4) "NOAA Ship Okeanos Explorer 2013 Remotely Operated Vehicle (ROV) Shakedown: ROV Video." *Gulf of Mexico 2012 Daily Updates RSS*. Web. 07 Apr. 2014

5) Ballard, Robert. "The JASON Remotely Operated Vehicle System" Woods Hole, MA 1993

6) "SeaFox: A Quicker, Cheaper, Safer Mine-hunting Capability." *Navy Live*. Web. 07 Apr. 2014.

7) Orejel, Luis. *Robotic Arm.*

   <https://grabcad.com/library/robotic-arm-7/files/Brazo/Gripper >

8) "OpenROV | Underwater Exploration Robots." *OpenROV | Underwater Exploration Robots*. Web. 22 Oct. 2014. <http://www.openrov.com/>.

9) "JW Fishers - ROV, Remote Operated Vehicles, Seaotter, Sealion, Metal Detectors, Sonar, Magnetometer, Pinger, Cable Tracker." *JW Fishers - ROV, Remote Operated Vehicles, Seaotter, Sealion, Metal Detectors, Sonar, Magnetometer, Pinger, Cable Tracker*. Web. 22 Oct. 2014. <http://www.jwfishers.com/rov.htm>.

10) "Monterey Bay Aquarium Research Institute." ROV Ventana. Web. 22 Oct. 2014.

<http://www.mbari.org/dmo/vessels_vehicles/ventana/Ventana_Launch%202.jpg>.

11) "ACE-ROV." *ACE-ROV*.Web. 22 Oct. 2014. <http://poisson.me.dal.ca/~dp_10_02/Design.htm>

12) MacQuarrie, Iain. "Diving Bells and Observation Chambers." *Diving Bells and Observation Chambers*. DivingHeritage, Web. 23 Nov. 2014. <http://www.divingheritage.com/chambers.htm>.

13) Harris, Brayton. "Submarine History 1580-1869: Timeline of Submarine Development." *Submarine History 1580-1869: Timeline of Submarine Development*. NOVA, Web. 21 Nov. 2014. <http://www.submarine-history.com/NOVAone.htm>.

14) Carothers, Kyle. "NOAA Ocean Explorer: Deep Scope Background." *NOAA Ocean Explorer Podcast RSS 20*. NOAA, Web. 23 Nov. 2014. <http://oceanexplorer.noaa.gov/explorations/04deepscope/background/deeplight/media/diagram3.html>.

15) "Home Built ROV Forum." Web. 10 Nov. 2014 <http://www.homebuiltrovs.com/rovforum/viewtopic.php?f=18&t=258>

16) "Futaba 6EXA 6 Channel FM Transmitter." RC Universe, Web. 10 Nov. 2014 <http://www.rcuniverse.com/magazine/article_display.cfm?article_id=556>

17) Konstad, Christopher. "Rovsuite/monterey." *GitHub*. N.p., n.d. Web. 23 Nov. 2014. <https://github.com/rovsuite/monterey>.

Appendix I: Electrical Block Diagram

This diagram illustrates the proposed functional block diagram for the ROV. As shown, topside will consist of a power supply and laptop running the control interface. Onboard the ROV, several subsystems exist. Among the systems there is a voltage conversion and power distribution system, a sensor array, brushless motor speed controllers and an onboard Microcontroller to interface between command signals and ROV system operations. In addition, there is a camera that will be directly wired to the control station to provide visual feedback.

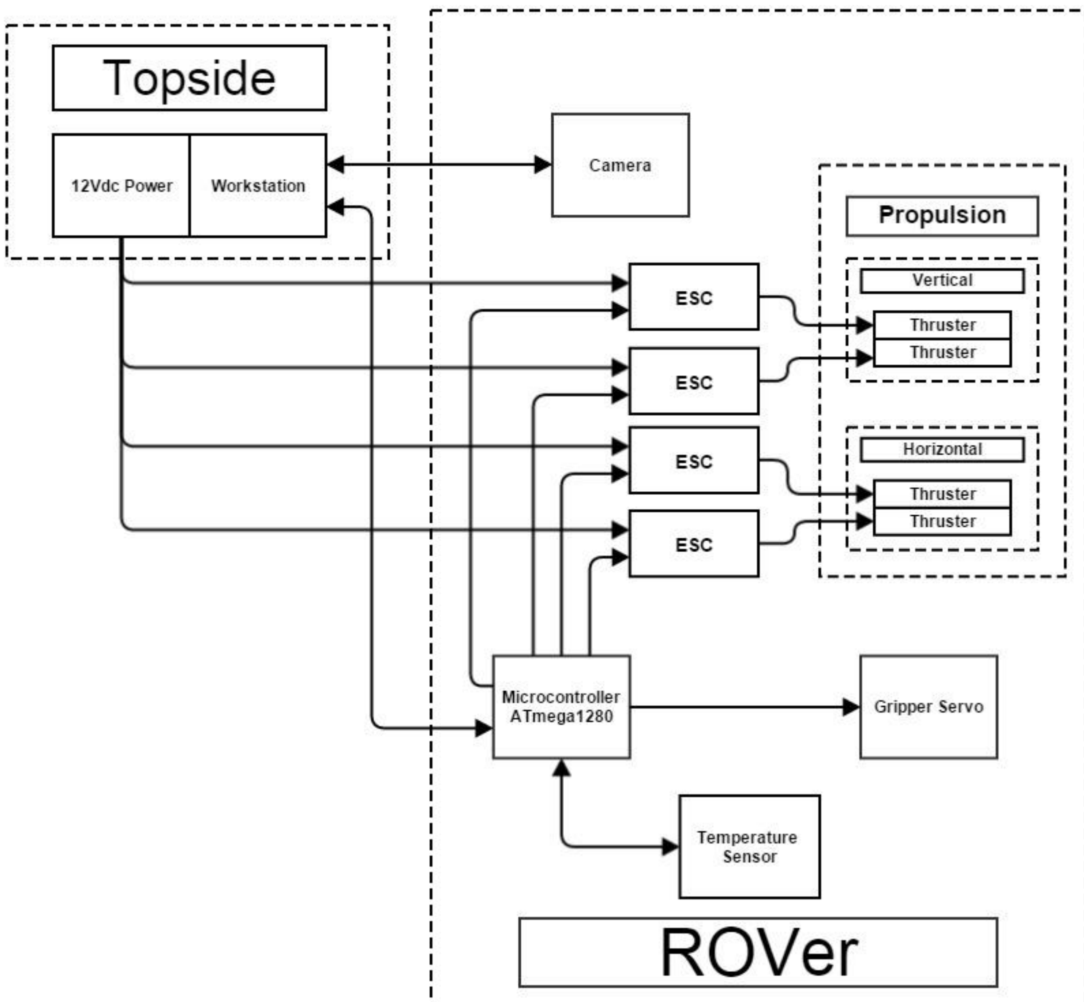

Figure 20: Functional Block Diagram

Appendix B: User Manuals

Appendix B.1: English

Volume

1

FLORIDA INTERNATIONAL UNIVERSITY

Mechanical Engineering Department

ROVer1.0

User Manual

FLORIDA INTERNATIONAL UNIVERSITY

ROVer 1.0 User Manual

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Chapter

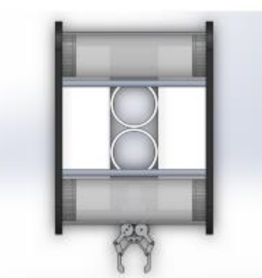
1

Meet the ROV

The FIU underwater ROVer is a new and innovative remotely operated vehicle for use in underwater exploration and survey.

The FIU underwater ROVer consists of an easily modified chassis and user-customizable control software run in MATLAB. The ROV is driven by four independent thrusters, two vertical and two horizontal. In addition, the front mounted gripper provides for grasping and positioning as necessary.

The goal of this project was to develop an economic and versatile alternative to the current ROV market, and we have succeeded.



Initial Setup

The most vital aspect of operation is maintaining a **waterproof** integrity. It is important to ensure a tight seal on all the endcaps prior to submerging the ROV.

Prior to Operation:

1. **Verify all cables are connected properly:**
    a. **ESC control wires connected to pins 2, 3, 4, and 5 of the Arduino.**
    b. **Servo control wire connected to pin 6.**
    c. **Servo power is to be connected to 5V pin.**
    d. **Temperature sensor is to be connected to 3.3V**
    e. **Temperature SDA connects to pin A4**
    f. **Temperature SCL connects to pin A5**
    g. **Ground wires connected to GND pin.**
    h. **All other cable splices secure.**
2. **Slide control hardware into the electronics tube.**
3. **Inspect and apply silicon grease to O-rings, if necessary.**
4. **Place endcaps and push until secured, while air slowly bleeds from the electronics housing.**

General tips

Water leaking into the electronics tube can be catastrophic! Test for water-tightness by first submerging the ROV for a short time without powering on. Raise the sub and verify no water has entered the housings. If water has entered, re-inspect the O-rings and re-apply grease if needed. If no water has entered, proceed with operation.

How to Connect the ROV

Only once verified water-tight and ready to submerge, can the next stage can be completed. *Note: If performing testing out of water, a water-tight seal is not required.*

Connecting the ROV:

1. **Spool out the tether and verify its integrity.**
2. **Connect the male USB to the Laptop USB port.**
    a. **Verify the Arduino is recognized in the device manager window.**
    b. **Note the COM port in the device manager window.**
3. **Connect the gamepad to the Laptop USB port.**
4. **Connect the power line to the battery:**
    a. **Black connects to (-)**
    b. **Red connects to (+)**
    c. **Once connected, note the chirping of the unarmed ESCs**
5. **Run the control software in MATLAB**
    a. **Visually verify the gripper cycles positions**
    b. **Audibly verify the arming of the ESCs**
        i. **Marked by a distinct 3 tone chime**
    c. **Verify the control software is reporting temperature**
6. **The ROV is now connected and ready to operate!**

Troubleshooting

If any problems are encountered in the preceding setup procedures, consult the troubleshooting section on page 5 for more help.

How to Control the ROV

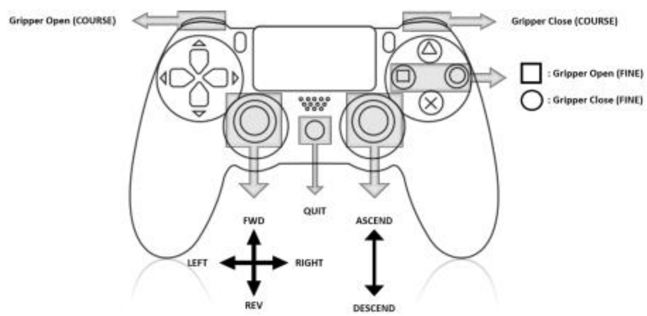


FIGURE 1: Gamepad Control Scheme

Controlling the Underwater ROVer is easy with any analog joystick or gamepad.

Out of the box, the ROVer is programmed to work with any SONY PLAYSTATION® type gamepad. The dual analog sticks and copious button options provide a perfect means to control the sub. Figure 1 shows the control layout for this control scheme.

Designed to be customizable, the control scheme can be modified within MATLAB. Additionally, any joystick or gamepad can be used with some modifications made in the control code.

Try this: The control code is well documented so feel free to modify it to suit your needs. Pin assignments, throttle values, and gripper movement resolution are just some of the parameters that you can tweak. This platform is designed from the ground up to be easily customized, so take advantage of it.

Note

Obtain and install correct driver software from manufacturer before interfacing any joystick or gamepad with the control software.

Troubleshooting Guide

If any problems occur that are NOT solved by the following troubleshooting guide, please contact the manufacturer for further guidance.

LEAKS

1. **Visually inspect O-rings**
    a. **Replace worn or cracked O-rings.**
    b. **Re-apply silicone grease, if needed.**
2. **Visually inspect endcaps**
    a. **Take care to closely inspect wire run area.**
    b. **Seal any leaks using RUSTOLEUM® flexible rubber sealant.**
3. **For 3D printed endcaps:**
    a. **Removing O-rings and soaking endcap in acetone may help to reseal any separation that may have developed.**
4. **Re-perform submergence leak test before next operation.**

ERROR CODES

1. **"Error using Control_w_joystick_V3_Analog_2014_added_temp_sensor (line 30) Joystick is not connected."**
    a. **Ensure gamepad is connected via USB port.**
    b. **Verify correct drivers are installed.**
2. **"Error using Control_w_joystick_V3_Analog (line 59) No Arduino hardware is found on port COM3."**
    a. **Ensure that tether is connected via USB port.**
    b. **Verify Arduino COM PORT; if needed change line for value to 'COM#' with # corresponding to the COM PORT defined in device manager**

3. "No appropriate method, property, or field servoAttach for class arduino."
    a. Verify the version of MATLAB installed.
    b. Run the correct control code script:
        i. For MATLAB 2014:
            1. Control_w_joystick_V3_Analog_2014_added_temp_sensor.m
        ii. For MATLAB 2013:
            1. Control_w_joystick_V3_Analog.m
4. "Error using Control_w_joystick_V3_Analog_2014_added_temp_sensor (line 190) Failed to read 2 uint8 value(s) from the device."
    a. Verify temperature sensor module is connected correctly:
        i. 3.3V
        ii. GND
        iii. SDA to pin A4
        iv. SCL to pin A5
    b. If no temperature sensing module is installed:
        i. Modify code by commenting out lines:
            1. 64, 65
            2. 190, 191, 192
            3. 196, 197, 206, 207, 216, 217, 226
            4. 227, 236, 237, 246, 247, 256, 257
            5. 268, 269, 280, 281, 292, 293
            6. 304, 305, 316, 317, 318

Appendix B.2: Spanish

Volume

1

UNIVERSIDAD INTERNACIONAL DE FLORIDA

Departamento de Ingenieria Mecanica

ROVer 1.0

Manual de Usario

UNIVERSIDAD INTERNACIONAL DE FLORIDA

Manual de UsuarioROVer 1.0

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Chapter

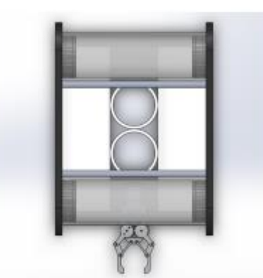
1

El ROV

El explorador submarino FIU es un vehículo operado remotamente nuevo e innovador para el uso en la encuesta y de exploración submarina.

El FIU ROVer submarino consiste en un chasis modificado fácilmente y software de control personalizables por el usuario en MATLAB. El ROV es impulsado por cuatro motores independientes, dos verticales y dos horizontales. Además, la pinza delantera montada proporciona para agarrar y posicionamiento según sea necesario.

El objetivo de este proyecto fue desarrollar una alternativa económica y versátil para el mercado actual de ROV, y hemos tenido éxito.



Configuración inicial

El aspecto más importante de la operación es mantener una integridad **impermeable**. Es importante asegurar un cierre hermético en todos los tapones antes de sumergir el ROV.

Antes de la operación:

1. **Verificar todos los cables estén conectados correctamente:**
    a. **ESC control cables conectados a los pines 2, 3, 4 y 5 de la Arduino.**
    b. **Cable de control del servo conectado al pin 6.**
    c. **Servo poder está para ser conectado al pin de 5V.**
    d. **Sensor de temperatura es conectarse a 3.3V**
    e. **Temperatura SDA se conecta al pin A4**
    f. **Temperatura SCL se conecta al pin A5**
    g. **Cables conectados al pin GND tierra.**
    h. **Empalmes de todo otro cable seguro.**
2. **Hardware de control deslizante en el tubo electrónica.**
3. **Examine y aplique grasa de silicona para anillos O, si es necesario.**
4. **Coloque los tapones y empuje hasta que quede asegurado, mientras que el aire lentamente sangra de la caja electrónica.**

Consejos generales

Fugas en el tubo de electrónica pueden ser catastrófico. Prueba de estanqueidad sumergiendo primero el ROV por un corto tiempo sin encender. Levantar el submarino y verifique que no ha entrado agua en las viviendas. Si ha entrado agua, vuelva a inspeccionar los O-rings y vuelva a aplicar grasa si es necesario. Si no ha entrado agua, proceder con la operación.

Cómo conectar el ROV

Sólo una vez verificado hermético y listo para sumergirse, puede la próxima etapa puede ser completada. *Nota: si se realiza la prueba fuera del agua, no es necesario un sello hermético.*

Conectar el ROV:

1. **Carrete hacia fuera la correa y verificar su integridad.**
2. **Conecte el USB macho al puerto USB del ordenador portátil**
3. **Conectar el gamepad para el puerto USB del ordenador portátil**
4. **Conecte la línea de alimentación a la batería:**
    a. **Negro se conecta al (-)**
    b. **Red conecta (+)**
    c. **Una vez conectado, tenga en cuenta el canto de las ESCs desarmados**
5. **Ejecute el software de control en MATLAB**
    a. **Verificar visualmente las posiciones de los ciclos de pinza**
    b. **Audiblemente verificar la activación de las CES**

1. **i Marcado por un carillón de 3 tonos distintos**
    c. **Informa verificar el software de control de temperatura**

6. **El ROV ahora está conectado y listo para funcionar.**

Solución de problemas

Si se encuentran problemas en los procedimientos de configuración anteriores, consulte la sección solución de problemas en la página 5 para obtener más ayuda.

Cómo controlar el ROV

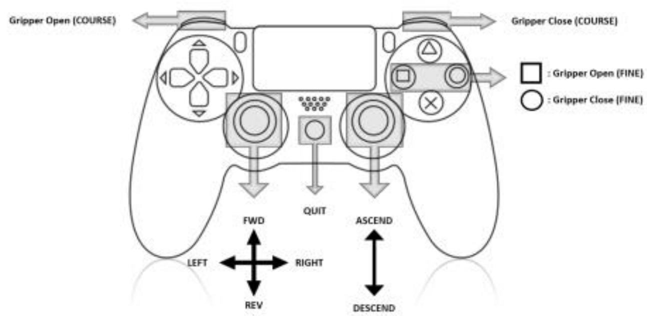


FIGURA 1: Esquema de Control Gamepad

Controlar al explorador submarine es facil con gamepad o joystic analogico

Fuera de la caja , el ROVer está programado para funcionar con cualquier gamepad tipo SONY PLAYSTATION ®. Las dos sticks analógicos y copiosa botón opciones ofrecen que un perfecto significa controlar el submarino. La figura 1 muestra el esquema de control para este esquema de control.

Diseñado para ser configurable, el esquema de control pueden ser modificados dentro de MATLAB. Además, puede utilizarse cualquier joystick o gamepad con algunas modificaciones en el código de control.

Prueba esto: El código de control está bien documentado así que siéntete libre para modificar para adaptarlo a sus necesidades. Asignaciones de pines, valores del acelerador y resolución del movimiento pinza son sólo algunos de los parámetros que pueden modificar.Esta plataforma está diseñada desde cero para ser fácilmente modificado, así que aprovechad.

Nota

Obtener e instalar software de controlador correcto del fabricante antes de entretela cualquier joystick o gamepad con el software de control..

Guía de solución de problemas

Si cualquier problemas que no son solucionados por la siguiente guía de localización de averías, póngase en contacto con el fabricante para más orientación.

FUGAS

1. **Inspeccione visualmente los O-rings**
    a. **Substituir gastadas o rotas O-rings.**
    b. **Re Aplique grasa de silicona, si es necesario.**
2. **Inspeccione visualmente los tapones**
    a. **Cuidar a inspeccionar estrechamente cable zona.**
    b. **Sellar fugas usando RUSTOLEUM ® sellador de goma flexible.**
3. **Para 3D impreso los tapones:**
    a. **Quitar anillos y tapón empapado en acetona pueden ayudar a sellar cualquier separación que puede haber desarrollado.**
4. **Volver a realizar la prueba de fuga de inmersión antes de la operación siguiente.**

CÓDIGOS DE ERROR

1. **"Error usando Control_w_joystick_V3_Analog_2014_added_temp_sensor (línea 30) Joystick no está conectado."**
    a. **Gamepad Asegúrese de que está conectado vía puerto USB**
    b. **Verificar que están instalados los controladores correctos.**
2. **"Error usando Control_w_joystick_V3_Analog (línea 59) hardware Arduino no se encuentra en el puerto COM3."**

a. **Asegúrese de que correa está conectado vía puerto USB**

b. **Verificar Arduino COM PORT; si es necesario cambiar la línea el valor ' COM #' con # de correspondiente al puerto COM definidos en el administrador de dispositivos**

3. **"Ningún método apropiado, propiedad o campo servoAttach para arduino clase."**

    a. **Verificar la versión de MATLAB instalado.**

    b. **Ejecutar el script de control correcto código:**

        i. **i Para el año 2014 MATLAB:**

            1. **Control_w_joystick_V3_Analog_2014_added_temp_sensor.m**

        ii. **Para MATLAB 2013:**

            1. **Control_w_joystick_V3_Analog.m**

4. **"Error usando Control_w_joystick_V3_Analog_2014_added_temp_sensor (línea 190) no pudo leer 2 uint8 valores desde el dispositivo."**

    a. **Módulo de verificar la temperatura del sensor está conectado correctamente:**

        i. **3.3V**

        ii. **GND**

        iii. **SDA al pin A4**

        iv. **SCL a pin A5**

b. **Si no está instalada ningún módulo de detección de temperatura:**

i. **Modificar código comentando las líneas:**

1. **64, 65**
2. **190, 191, 192**
3. **196, 197, 206, 207, 216, 217, 226**
4. **227, 236, 237, 246, 247, 256, 257**
5. **268, 269, 280, 281, 292, 293**
6. **304, 305, 316, 317, 318**

Appendix C: MATLAB Control Code

```
% OVERHAULED TO SUPPORT MATLAB2014 added i2c temperature sensor
clc; % Clears screen
COM_PORT = 'COM3';
POLL_RATE = 0.1; % Controller read rate

% Pin Assignments
LEFT = 3; %ziptied
RIGHT = 2;
FWD = 4; %ziptied
BACK = 5;
GRIPPER = 6;

% Gripper Contstants
OPEN = 20/180; % Open Servo Angle
CLOSED = 150/180; % Closed Servo Angle
MID = 90/180; % Neutral Servo Angle
GRIPPER_RES = 5/180; % Gripper Motion Resolution

% Thruster Constants
MAX_THRUST = 80/180; %  90 +/- MAX_THRUST
MAX_FWD_THRUST = 170/180;
MAX_REV_THRUST = 60/180;
ZERO_THRUST = 90/180;
THRUST_COUNTER = 1;
THRUST_RES = 2/180;

% Set up joystick
disp('Connecting to Controller... ');
PS4 = vrjoystick(1);
pause(1);
fprintf('Connected!\n')
%disp(caps(PS4));

% PS4 controller mapping

% 1 - SQUARE
% 2 - X
% 3 - O
% 4 - TRIANGLE
% 5 - L BUMPER
% 6 - R BUMPER
% 7 - L TRIGGER
% 8 - R TRIGGER
% 9 - SHARE
% 10 - OPTIONS
% 11 - LS
% 12 - RS
% 13 - PS BUTTON
% 14 - TOUCHPAD
```

```
% Axis 1 - Left Stick - Horizontal, Left = -1, Right = 1
% Axis 2 - Left Stick - Vertical, Up = -1, Down = 1
% Axis 3 - Right Stick - Horizontal, Left = -1, Right = 1
% Axis 4 - Left Trigger - Pressed = 1, Realeased = -1
% Axis 5 - Right Trigger - Pressed = 1, Realeased = -1
% Axis 3 - Right Stick - Vertical, Up = -1, Down = 1

disp('ROV Connection:');
ROV = arduino(COM_PORT)
fprintf('Connected!\n')

% Create Temperature Sensor Object on i2c Bus
tmp102 = i2cdev(ROV, '0x48');
write(tmp102, 0, 'uint8');

% Attach Thruster ESCs
LEFT_THRUSTER = servo(ROV, LEFT);
RIGHT_THRUSTER = servo(ROV, RIGHT);
FWD_THRUSTER = servo(ROV, FWD);
BACK_THRUSTER = servo(ROV, BACK);

% MATLAB 2013
% ROV.servoAttach(LEFT); % Horizontal Left Thruster
% ROV.servoAttach(RIGHT); % HR
% ROV.servoAttach(FWD); % VF
% ROV.servoAttach(BACK); % VB

% Attach Gripper Servo
% ROV.servoAttach(GRIPPER);
GRIPPER_SERVO = servo(ROV, GRIPPER);

fprintf('Cycling Gripper...\n')

% Cycling Gripper
% ROV.servoWrite(GRIPPER,OPEN); % Gripper Open
% pause(1);
% ROV.servoWrite(GRIPPER,CLOSED); % Gripper Closed
% pause(1);
% ROV.servoWrite(GRIPPER,OPEN); % Gripper Open
% pause(1);
% ROV.servoWrite(GRIPPER,MID); % Gripper Neutral

writePosition(GRIPPER_SERVO, OPEN);
pause(1);
writePosition(GRIPPER_SERVO, CLOSED);
pause(1);
writePosition(GRIPPER_SERVO, OPEN);
pause(1);
writePosition(GRIPPER_SERVO, MID);


% Arming ESCs
fprintf('Arming ESCs... ')

% ROV.servoWrite(LEFT,0);
% ROV.servoWrite(RIGHT,0);
```

```
% ROV.servoWrite(FWD,0);
% ROV.servoWrite(BACK,0);

writePosition(LEFT_THRUSTER, 0);
writePosition(RIGHT_THRUSTER, 0);
writePosition(FWD_THRUSTER, 0);
writePosition(BACK_THRUSTER, 0);

pause(1.5);

% ROV.servoWrite(LEFT,180);
% ROV.servoWrite(RIGHT,180);
% ROV.servoWrite(FWD,180);
% ROV.servoWrite(BACK,180);

writePosition(LEFT_THRUSTER, 1);
writePosition(RIGHT_THRUSTER, 1);
writePosition(FWD_THRUSTER, 1);
writePosition(BACK_THRUSTER, 1);

pause(1.5);

% ROV.servoWrite(LEFT,90);
% ROV.servoWrite(RIGHT,90);
% ROV.servoWrite(FWD,90);
% ROV.servoWrite(BACK,90);

writePosition(LEFT_THRUSTER, 0.5);
writePosition(RIGHT_THRUSTER, 0.5);
writePosition(FWD_THRUSTER, 0.5);
writePosition(BACK_THRUSTER, 0.5);

pause(1.5);

disp(' Armed!');

pause(1);

disp('Program started. Use PS Button or CTRL^C to end');

pause(2);

while (button(PS4, 13) ~= 1) % Keep program running until PS button is
pressed

%     UNCOMMENT TO DISPLAY CONTROLLER VALUES FOR MAPPING
%     disp(axis(PS4, 1));
%     disp(axis(PS4, 2));
%     disp(axis(PS4, 3));
%     disp(axis(PS4, 4));
%     disp(axis(PS4, 5));
%     disp(axis(PS4, 6));
%
%     disp(button(PS4, 1));
%     disp(button(PS4, 2));
%     disp(button(PS4, 3));
```

```
%     disp(button(PS4, 4));
%     disp(button(PS4, 5));
%     disp(button(PS4, 6));
%     disp(button(PS4, 7));
%     disp(button(PS4, 8));
%     disp(button(PS4, 9));
%     disp(button(PS4, 10));
%     disp(button(PS4, 11));
%     disp(button(PS4, 12));
%     disp(button(PS4, 13));
%     disp(button(PS4, 14));

%     pause(POLL_RATE);
%     clc;

    % Store instantaneous axis/button readings
    PS4_TURN = axis(PS4, 1);
    PS4_DRIVE = axis(PS4, 2);
    PS4_DIVE = axis(PS4, 6);
    PS4_OPEN_COURSE = button(PS4, 5);
    PS4_CLOSE_COURSE = button(PS4, 6);
    PS4_OPEN = button(PS4, 1);
    PS4_CLOSE = button(PS4, 3);
    PS4_PITCH_DOWN = button(PS4, 4);
    PS4_PITCH_UP = button(PS4, 2);

    % Poll temperature sensor, convert, and display results
    data = read(tmp102, 2, 'uint8');
    temperature_celsius = (double(bitshift(int16(data(1)), 4)) +
double(bitshift(int16(data(2)), -4))) * 0.0625;
    temperature_f = (temperature_celsius*1.8)+32;

    if (PS4_DRIVE < -0.2)
        clc;
        disp('Compartment Temperature is:');
        disp(strcat(int2str(temperature_f),' ' , ' degrees
Fahrenheit'));
        disp('Forward');
        %disp(ZERO_THRUST + round(abs(PS4_DRIVE)*MAX_THRUST));
        disp(strcat('Thrust = ', int2str(100*abs(PS4_DRIVE)), '%'));
        writePosition(LEFT_THRUSTER, ZERO_THRUST -
abs(PS4_DRIVE)*MAX_THRUST); %change motor direction with +/-
        writePosition(RIGHT_THRUSTER, ZERO_THRUST +
abs(PS4_DRIVE)*MAX_THRUST); %change motor direction with +/-

    elseif (PS4_DRIVE > 0.2)
        clc;
        disp('Compartment Temperature is:');
        disp(strcat(int2str(temperature_f),' ' , ' degrees
Fahrenheit'));
        disp('Reverse');
        %disp(ZERO_THRUST + round(abs(PS4_DRIVE)*MAX_THRUST));
        disp(strcat('Thrust = ', int2str(100*abs(PS4_DRIVE)), '%'));
        writePosition(LEFT_THRUSTER, ZERO_THRUST +
abs(PS4_DRIVE)*MAX_THRUST); %change motor direction with +/-
```

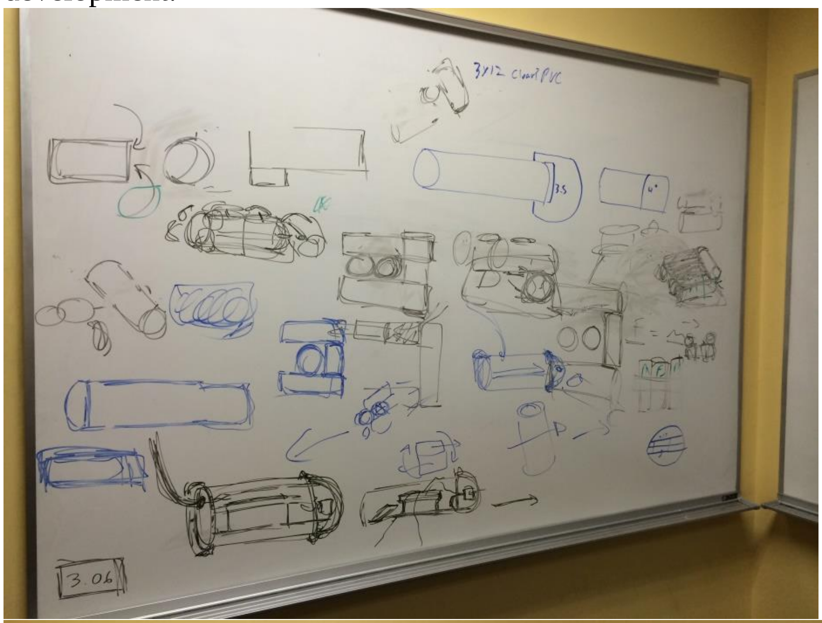
```
        writePosition(RIGHT_THRUSTER, ZERO_THRUST -
abs(PS4_DRIVE)*MAX_THRUST); %change motor direction with +/-

    elseif (PS4_TURN < -0.2)
        clc;
        disp('Compartment Temperature is:');
        disp(strcat(int2str(temperature_f),' ' , ' degrees
Fahrenheit'));
        disp('Turning Left');
        %disp(ZERO_THRUST + round(abs(PS4_TURN)*MAX_THRUST));
        disp(strcat('Thrust = ', int2str(100*abs(PS4_TURN)), '%'));
        writePosition(LEFT_THRUSTER, ZERO_THRUST -
abs(PS4_TURN)*MAX_THRUST); %change motor direction with +/-
        writePosition(RIGHT_THRUSTER, ZERO_THRUST -
abs(PS4_TURN)*MAX_THRUST); %change motor direction with +/-

    elseif (PS4_TURN > 0.2)
        clc;
        disp('Compartment Temperature is:');
        disp(strcat(int2str(temperature_f),' ' , ' degrees
Fahrenheit'));
        disp('Turning Right');
        %disp(ZERO_THRUST + round(abs(PS4_TURN)*MAX_THRUST));
        disp(strcat('Thrust = ', int2str(100*abs(PS4_TURN)), '%'));
        writePosition(LEFT_THRUSTER, ZERO_THRUST +
abs(PS4_TURN)*MAX_THRUST); %change motor direction with +/-
        writePosition(RIGHT_THRUSTER, ZERO_THRUST +
abs(PS4_TURN)*MAX_THRUST); %change motor direction with +/-

    elseif (PS4_DIVE < -0.2)
        clc;
        disp('Compartment Temperature is:');
        disp(strcat(int2str(temperature_f),' ' , ' degrees
Fahrenheit'));
        disp('Ascending');
        %disp(ZERO_THRUST + round(abs(PS4_DIVE)*MAX_THRUST));
        disp(strcat('Thrust = ', int2str(100*abs(PS4_DIVE)), '%'));
        writePosition(FWD_THRUSTER, ZERO_THRUST -
abs(PS4_DIVE)*MAX_THRUST); %change motor direction with +/-
        writePosition(BACK_THRUSTER, ZERO_THRUST -
abs(PS4_DIVE)*MAX_THRUST); %change motor direction with +/-

    elseif (PS4_DIVE > 0.2)
        clc;
        disp('Compartment Temperature is:');
        disp(strcat(int2str(temperature_f),' ' , ' degrees
Fahrenheit'));
        disp('Descending');
        %disp(ZERO_THRUST + round(abs(PS4_DIVE)*MAX_THRUST));
        disp(strcat('Thrust = ', int2str(100*abs(PS4_DIVE)), '%'));
        writePosition(FWD_THRUSTER, ZERO_THRUST +
abs(PS4_DIVE)*MAX_THRUST); %change motor direction with +/-
        writePosition(BACK_THRUSTER, ZERO_THRUST +
abs(PS4_DIVE)*MAX_THRUST); %change motor direction with +/-

    elseif (button(PS4, 1) == 1)
```

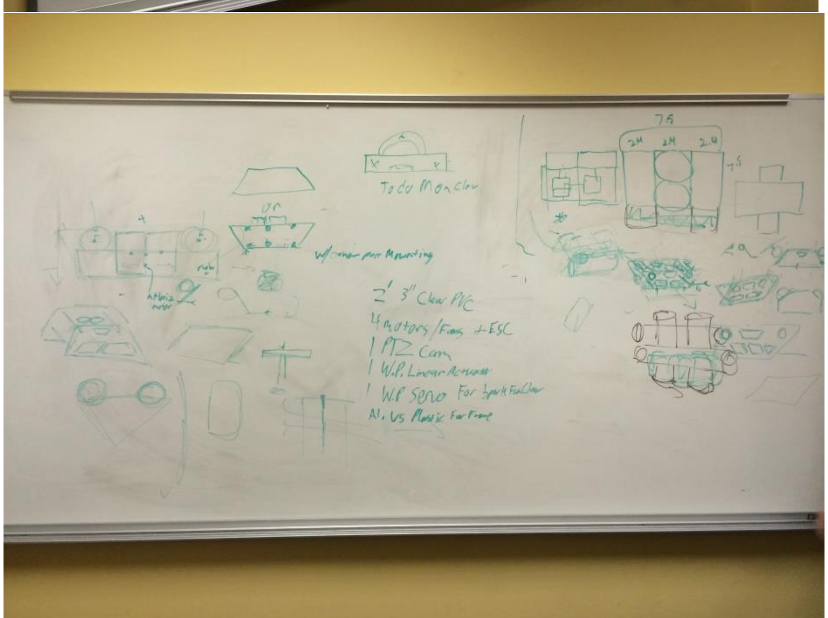
```
        clc;
        disp('Compartment Temperature is:');
        disp(strcat(int2str(temperature_f),' ' , ' degrees
Fahrenheit'));
        POS = readPosition(GRIPPER_SERVO);
        if POS > OPEN + GRIPPER_RES
            disp('Opening Claw');
            writePosition(GRIPPER_SERVO, POS - GRIPPER_RES);
        else
            disp('Claw Fully Open!');
        end

    elseif (button(PS4, 3) == 1)
        clc;
        disp('Compartment Temperature is:');
        disp(strcat(int2str(temperature_f),' ' , ' degrees
Fahrenheit'));
        POS = readPosition(GRIPPER_SERVO);
        if POS < CLOSED - GRIPPER_RES
            disp('Closing Claw');
            writePosition(GRIPPER_SERVO, POS + GRIPPER_RES);
        else
            disp('Claw Fully Closed!');
        end

    elseif (button(PS4, 5) == 1)
        clc;
        disp('Compartment Temperature is:');
        disp(strcat(int2str(temperature_f),' ' , ' degrees
Fahrenheit'));
        POS = readPosition(GRIPPER_SERVO);
        if POS > OPEN + 4*GRIPPER_RES
            disp('Opening Claw');
            writePosition(GRIPPER_SERVO, POS - 4*GRIPPER_RES);
        else
            disp('Claw Fully Open!');
        end

    elseif (button(PS4, 6) == 1)
        clc;
        disp('Compartment Temperature is:');
        disp(strcat(int2str(temperature_f),' ' , ' degrees
Fahrenheit'));
        POS = readPosition(GRIPPER_SERVO);
        if POS < CLOSED - 4*GRIPPER_RES
            disp('Closing Claw');
            writePosition(GRIPPER_SERVO, POS + 4*GRIPPER_RES);
        else
            disp('Claw Fully Closed!');
        end

    else
        clc;
        disp('Compartment Temperature is:');
        disp(strcat(int2str(temperature_f),' ' , ' degrees
Fahrenheit'));
```

```
        disp('Halt');
        disp('Input?');
        THRUST_COUNTER = 0; % Reset variable thrust and thrusters to
neutral
        writePosition(LEFT_THRUSTER, 0.5);
        writePosition(RIGHT_THRUSTER, 0.5);
        writePosition(FWD_THRUSTER, 0.5);
        writePosition(BACK_THRUSTER, 0.5);
     end

    % Poll temperature sensor, convert, and display results
    data = read(tmp102, 2, 'uint8');
    temperature_celsius = (double(bitshift(int16(data(1)), 4)) +
double(bitshift(int16(data(2)), -4))) * 0.0625;
    temperature_f = (temperature_celsius*1.8)+32;

    pause(POLL_RATE);

end

disp('Terminating program...');
pause(1);

writePosition(LEFT_THRUSTER, 0.5);
writePosition(RIGHT_THRUSTER, 0.5);
writePosition(FWD_THRUSTER, 0.5);
writePosition(BACK_THRUSTER, 0.5);
disp('Throttle OFF...');
pause(1);

writePosition(GRIPPER_SERVO, OPEN);
pause(1);
writePosition(GRIPPER_SERVO, MID);
disp('Claw in Neutral Position...');

pause(2);

clear('ROV');
close(PS4);
delete(instrfind({'Port'},{'COM3'})); %Stops use of COM port
clear;
clc;
disp('PROGRAM TERMINATED');
disp('Goodbye!');
```

Appendix D: Photographs of Project

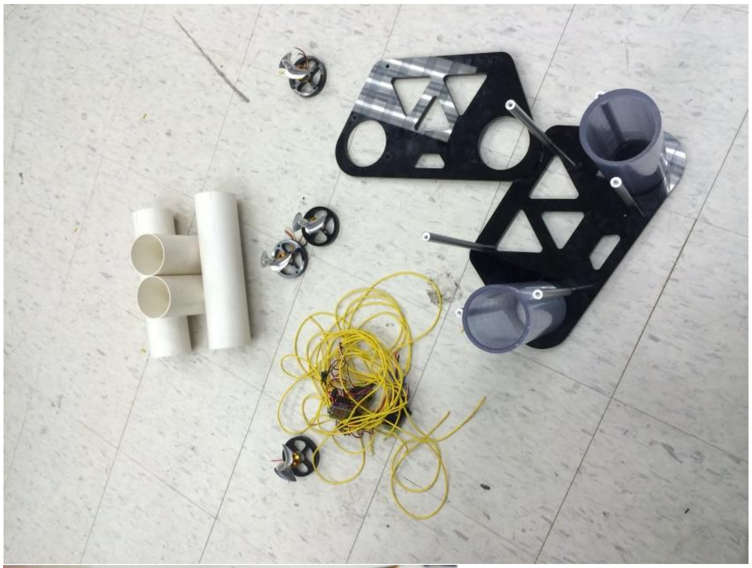
This Appendix is to serve as a quick guide through the brainstorming and construction process that occurred within the development of the ROV. Initially many rough concepts were proposed to account for thruster orientation and the motions that can be created with these configurations. Additionally the pressure vessels were accounted for through the development.

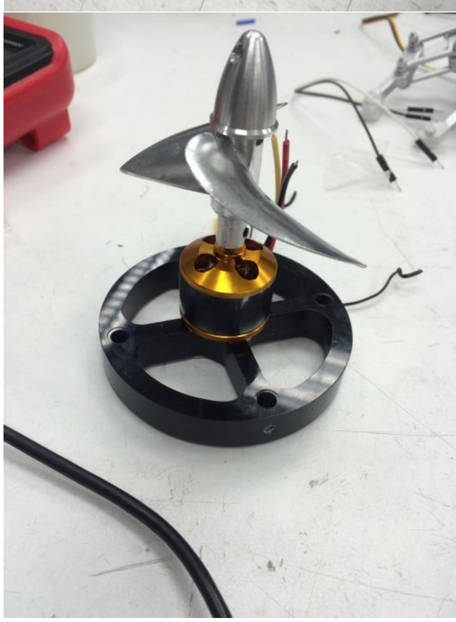




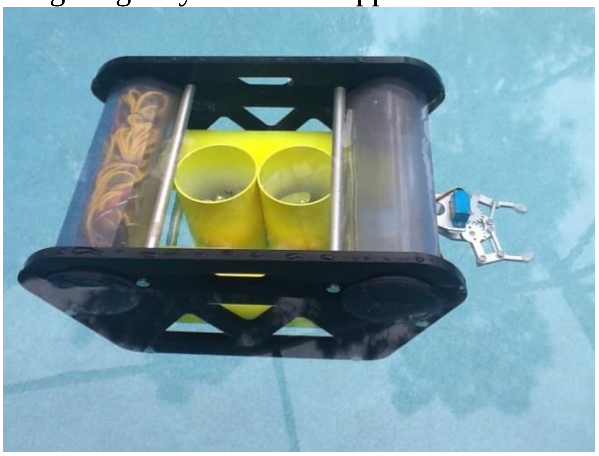
In looking at the 2nd whiteboard image some preliminary attributes to the concept developed can be seen. This includes an inverted version of the frame on the left side and the thruster configuration on the right section of the board.

Upon establishing a feasible design production and acquisition of the required components occurred and construction began in the following images.

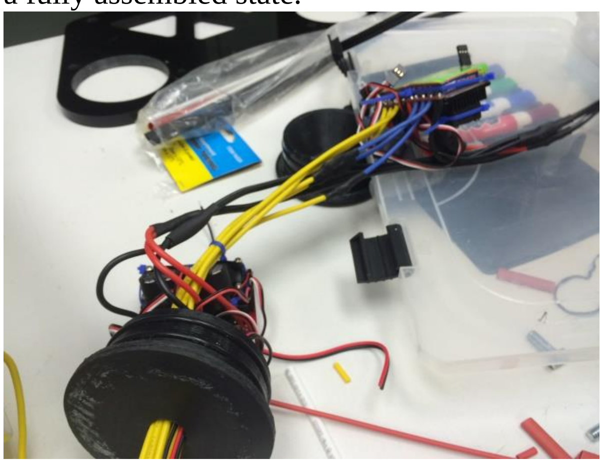




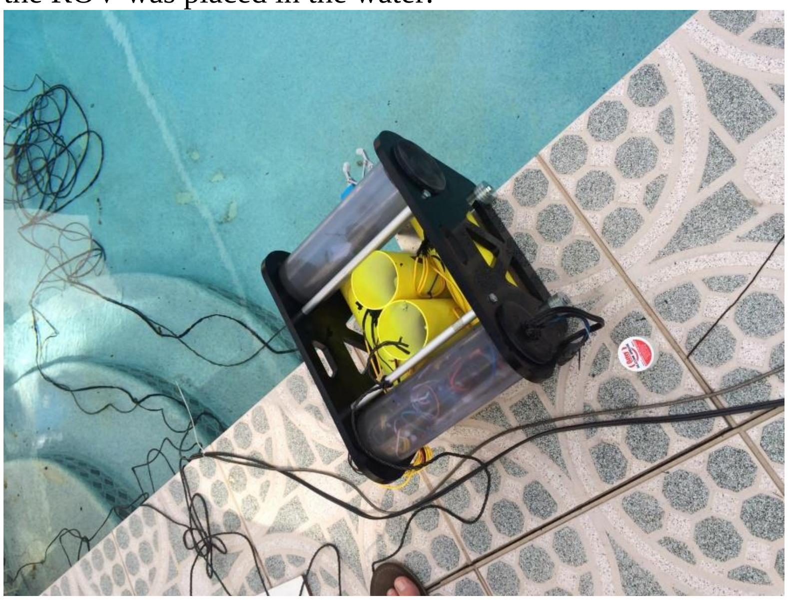
Upon reaching a near complete assembly of the ROV testing began to make some final configuration decisions such as determining the pressure vessels are sealed and how weighting may need to be applied for a flat near neutrally buoyant state.



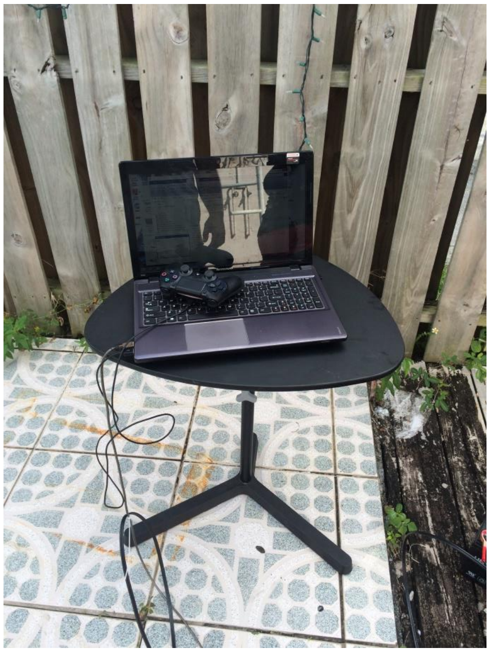
Upon establishing that the pressure vessels were sealed and adjusting weight as best as possible for the ROV to be naturally flat in its positioning construction resumed to reach a fully assembled state.



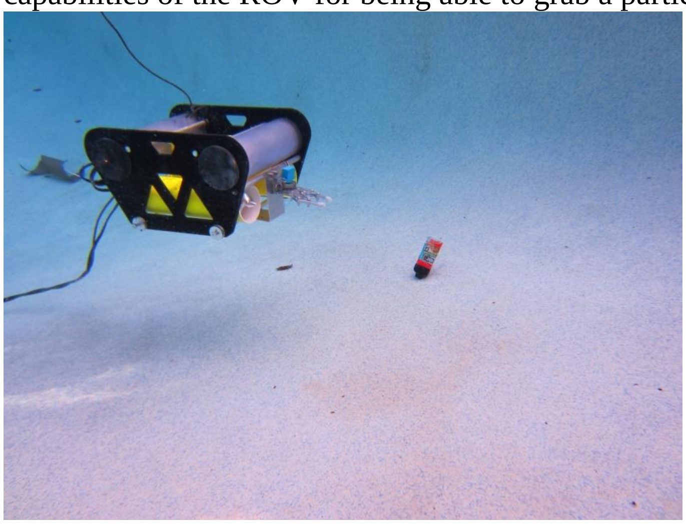
For final testing the ROV was prepped with lubing the O-rings with Silicone grease and the ROV was placed in the water.

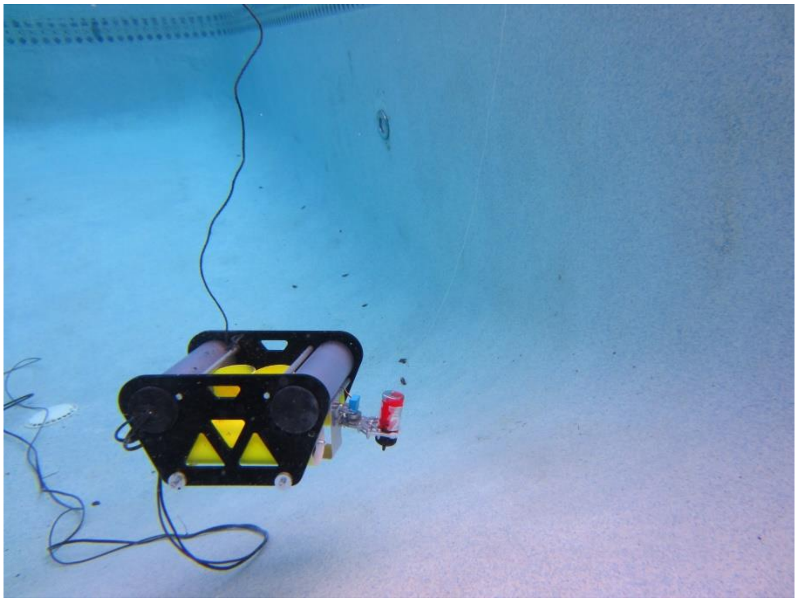


The operator was ready to begin testing with a laptop connected to the ROV and a Dual Joystick controller plugged into the laptop to allow more of an intuitive user input for ROV controls.



The operator navigated towards an object that was selected for retrieval and tested the capabilities of the ROV for being able to grab a particular object.




The object was successfully retrieved and in all shows that the project was a success.