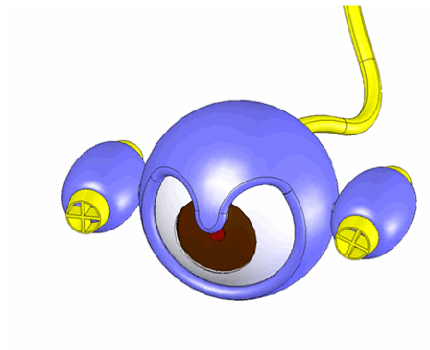
THE FLYING EYEBALL

AN UNDERWATER REMOTE OPERATED VEHICLE (ROV)



ME 191
SECOND SEMESTER SENIOR PROJECT
CSUS

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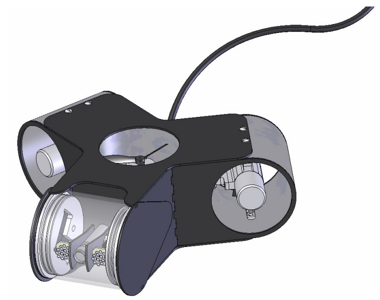
Abstract

Underwater remote operated vehicles (ROV) are used in a wide range of marine and oceanic industries. They are used in studying marine life, to build, inspect, and repair off-shore oil rigs, and explore downed ships to name a few uses. This group decided to design and fabricate a Remotely Operated Vehicle (ROV). Since the concept of an ROV is not innovatitive, it is the goal of the team to create a design that is creative as well as cost effective.

This report is the second for a one year senior project class. It includes descriptions of the ROV, a conceptual design analysis, drawings for fabrication, and the process we used to manufacture the ROV. Analyses performed on the ROV include design calculations, critical fits, tolerance studies, buoyancy and drag studies, and the effects of porpoising. The ROV was fabricated and assembled in order to confirm the validity of the previous semester's calculations and analyses. It is the expectation of the group that after completion of the project class, anyone will have the ability to duplicate the steps and procedures outlined in this report and obtain the same results in testing that is laid out in this report.

Introduction

Underwater remotely operated vehicles or ROV's, are used in a wide range of marine and oceanic industries. They are essential to deep sea exploration and research because they can travel to depths that human's cannot. ROV's have been known to be used to find downed planes and ships, search for drowned victims, and to repair and inspect large ships as well as off-shore oil rigs. These ROV's are usually very expensive and large in scale. There are smaller and less expensive ROV's on the market but they are still very costly and range from $5,000 to $7,000.



It was decided that this group would design and fabricate an inexpensive hobby size ROV. Its small size and cost range of $1500 to $2000 will allow a more diverse market than the ones already available. Once the ROV is built, it's the team's desire to market it for industrial as well as personal use. In the industrial arena the ROV can be used for inspection of docked ships, bridges, dams, or water pipers. For personal use the ROV can be used while fishing, filming underwater landscapes, as well filming for educational purposes. In the Industrial market, the tourist and dive industry is another consumer market for the ROV. Many tourists who take trips to exotic places to scuba dive would enjoy videos as a souvenir. These videos are normally expensive because the business has to pay for a water tight video camera, scuba equipment, and the cost of labor. These costs would be eliminated by purchasing a ROV and having it operated by the same employee that mans the boat.

A few of the ROV's specification include the ability to travel to a depth of 100 feet without critical failure, weigh less than 20 pounds so it can be transported by one person, and assemble and disassemble in two hours by two people. The ROV will be supplied power from an average household plug and this supply can be reproduced by using a generator or a 12 volt battery. It will be piloted by a remote for a hobby sized car and the video will be captured using a portable laptop. Aluminum will be used to make the motor and camera housings (pressure vessels) and ABS will be used to make the ROV's outer shell, propellers, and camera bay.

Results and Conclusions

There are two ways this senior project group were able to gage the success of this project. The first way to determined the success of the project was to finish fabrication and end up with a working ROV. This may not seem very complicated but it became an arduous task due to the tight fit of the design and the electrical wiring considerations. With this in mind the project was built and it was taken for a test run on Monday 09, 2005 in the Dolphin Dive Center pool. The ROV was operated for an hour and a half and there were no major failures to the ROV or the control system. In this primary criterion the group has been successful.

The second criterion involves the ability for an engineering group to set goals and specifications and by the end of the project they need to prove they have met most, if not all, of these specifications. The specifications set at the beginning of the project consist of a depth limit, weight limit, leak requirement, and assembly time limit. These were imperative because the ROV is to be marketed to a base that needs the ROV to be simple as well as transportable. The depth limit set by the group was necessary due to design complexity as well as component cost. The depth specification was 100 feet; this spec was not tested at the time the project because the group could not find dive equipment and a body of water in enough time. The ROV was put into a 9 foot deep pool and it survived the leakage specification. The ROV was run for about one and a half hours without having any leakage in the pressure vessels.

The weight and assembly specification was tested and had mixed results. The weight of the robot was to be no more than 20 lbs and the ROV actual weight was 2lbs. The assembly time, however, was severely underestimated for the prototype. It was discovered by actually keeping track of the time that the prototype was assembled in 60 hours. Although this is a major fall back, it was not critical because it was the first run on the design. There were many things that the team could have done better, such as design of certain components that would ease assembly time. The team believes that after the ‘kinks’ of the prototype are revised, the actual assembly time would be 3 hours by two people or 6 hours by one.

In reflection and analysis, the ROV team met both of its objectives to the best of its ability. As with any Engineer in Training, there are set backs and delays and redesigns that become necessary to fully develop a project. Since this project was very complex, it has to be expected that complications will arise and all criterion may not be met exactly. As with all engineering projects, whether graded or not, you analyze and work to get it right in the least amount of time.

Design Criteria

The ROV project was inspired by a desire to create a cost effective vision system capable of operating underwater. The specifications for this robot involve the depth it will travel, the method which the ROV will be piloted, and the serviceability of the ROV. Within each of these headings is a long list of design specification and trade-offs to make these specifications obtainable.

The robot has been designed to operate at a maximum depth of one hundred feet without more than 10 cc's of water entering the pressure vessels within a 24 hour period to avoid critical failure. This depth was decided upon mainly due to the cost of the components to handle signal transmission as well as pressure. Power over a short distance can be transmitted using DC current, but over long distances it will dissipate. In order to extend the distance the power would transmit, taking AC current and transforming it into DC at the robot itself became the best option. Unfortunately, this would cause an increase in the size of the pressure vessel in the robot, which raises the cost; this is undesirable for the given specifications. Due to this limitation the ROV will have to run off DC power converted topside and run over the length of the tether. Power loss is important because if the ROV loses power it will have to be pulled up by the tether. Pulling on the tether will cause stress and it could break. Just as transmission of power is an issue, the possibility of video signal degradation over the cable distance is also an issue. Video signal transmission through the line becomes increasingly lower quality as the length of the line it travels increases. If the ROV loses video feed then the objective of the ROV is lost.

Transmission of power and signal is just one issue that effects the depth limitation. Since the ROV will travel a one hundred foot depth, pressure equal to 43 psi will press against the ROV. All of the materials and pressure vessels must survive that pressure without leaking to avoid critical failure; this is the second project specification. The aluminum motor vessels, acrylic pressure vessel and buoyant materials are the primary culprits of collapse and leak problems in the ROV. The aluminum motor pressure vessels are penetrated in three places; the motor wiring running out the rear, the vessel splits in half for serviceability, and a rotating shaft penetrates the front. The rear penetration will be fitted with an A.N fitting sealed with epoxy in the interior of the camera bay with a hose leading away from pressure vessel. There will be an O-ring to prevent leaking in the motor assembly separation where the ROV can be serviced. A mechanical seal on the shaft must prevent leaking from the dynamic motion of the shaft at up to 263 RPM in addition to the pressure of 43 psi**.** It must maintain that seal for more than two weeks of operation.

The last specification entails the ability to service as well as transport the ROV. The ROV will weigh no more than 20 pounds and assemble and disassemble in less than two hours by two people. This is an important specification because the marketing goal is to sell it to individuals and needs to be convenient to use. It is also necessary to have the ability to assemble and disassemble the robot by two people in two hours. This specification is necessary because if the ROV is too complicated to put together by the purchaser, they may return the product and the group would loose money. It is also important to have the ability to disassemble it for repair in a reasonable amount of time and cost due to labor. If the product is assembled before sold then it is necessary to reduce the assembly time in order to save on labor costs by the distributor.

Design Process

This senior project group's desire is to design a compact, low cost, underwater remotely operated vehicle capable of capturing high quality video of its underwater environments. Three priorities, compact design, low cost, and high quality video, guided the overall design and selection of manufacturing processes for this project. As you can see in Figure 1 the initial design was comprised of a biomemetic tail actuated by servos. After considering the porpoising effect of the flapping motion of the tail, it was concluded that this design would not provide a stable platform for recording video and would be expensive.

Figure 1

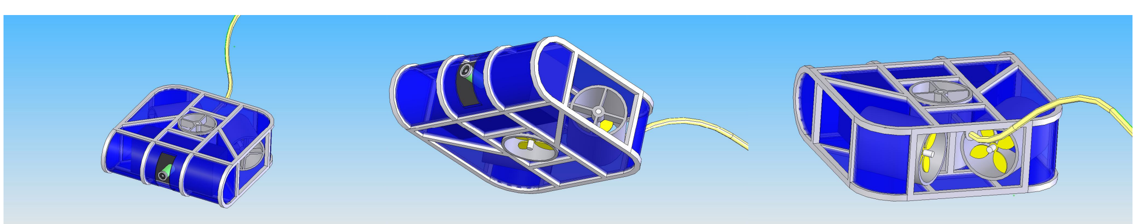


Figure 2

Figure 2 shows the second concept design, which was a three thruster, neutrally buoyant, design. The horizontal thrusters were set at 45° to be more compact. The frame was comprised of 1" diameter aluminum pipe which would be welded together, and the interstitial spacing would be filled with a blue polycarbonate. This required an extensive part-count and construction process for the frame. The overall dimensions where also larger than desired so the design was refined, taking the manufacturing process into consideration.

In Figure 3 you can see the second design was changed to use sheets of polycarbonate to sandwich the motor housings and pressure vessels using them as structural members. This reduced part count without reducing structural stiffness. After studying the material properties of polycarbonate it was found that tarnishing and cracking would occur if exposed extensively to ultra violate rays. Since the working environment for the ROV when it was out of the water is the deck of a ship. This would expose the ROV to direct sunlight and caused a need for a design change. Wiring the ROV and designing an appropriate penetration valve for the pressure vessels became an obstacle. Looking into A.N. fittings, it was obvious that every penetration into the pressure vessels increased the price and probability of a catastrophic failure. Also it was discovered that underwater lights and servos for the camera would cost upward of $500 and $3500 respectively.

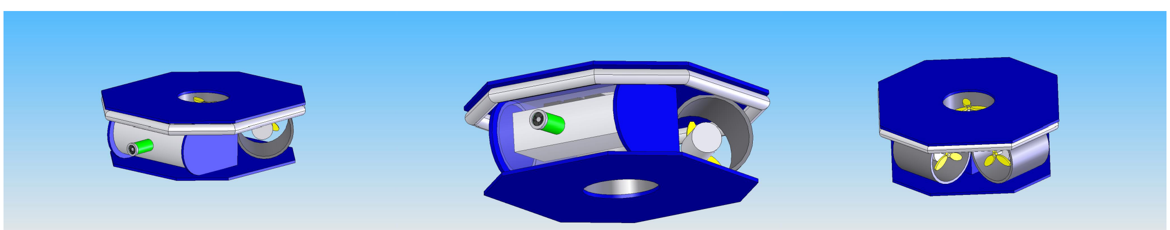
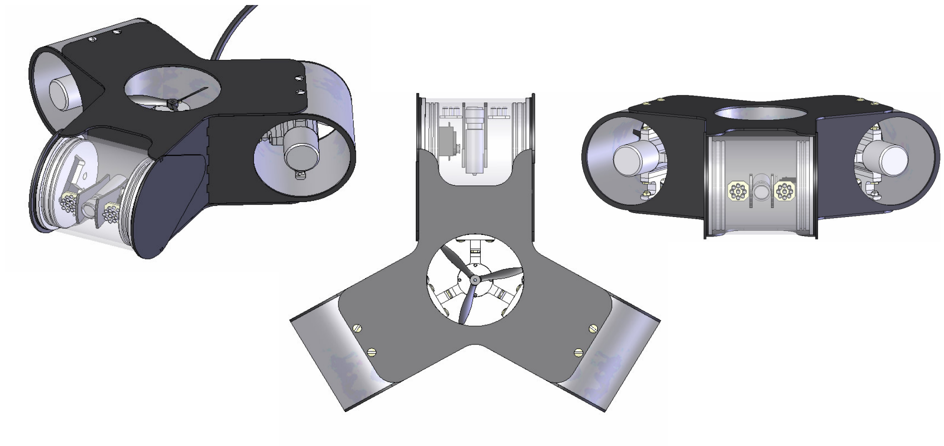


Figure 3

For the final design the frame material, now shown in black, was changed to ABS and the frame was streamlined to reduce drag when moving vertically in the water. The camera and lights, along with all the major electronics were moved into a single pressure vessel made from photo clear acrylic tubing with aluminum end caps. This reduced the amount of penetrations and eliminated the requirement for expensive underwater lights and servos. LED lights were chosen because of their ability to produce a large amount of light with very little heat. The pressure vessels and thruster housings are used as major structural supports simplifying assemblies and reducing part count and cost. The thrusters were moved to 120° from each other, this reduced thruster efficiency and provided symmetry in the frame when thrusting up or down in the water. Also, the frame is symmetric from top to bottom to reduce porpoising as explained in the porpoising section when thrusting horizontally in the water, as can be seen in Figure 4.



Now that the overall frame configuration was set the motor pressure vessels and mounts could be decided upon. Aluminum was chosen for its properties in salt water, and originally stainless steel bolts were going to be used to mount the frame and motor supports but this would create a dielectric effect causing corrosion in a salt-water environment. Because all the pressure vessels had a negative pressure it was decided that nylon bolts could be used without worry of failure in shear or tension because they were not under direct stress on the pressure vessels. For the motor mounts the diameter of the bolt was increased to 0.5” to account for stress in shear when the thruster is at full forward. These industrial grade nylon bolts have impressive properties of strength but are far lighter than stainless steel helping in the overall buoyancy of the robot. After all the material, cost, and design considerations the ROV was complete. The final product is a compact, stable robot that can be manufactured at a low cost.

Incorporation of Concurrent Engineering Techniques

The Flying Eyeball team has used many facets of concurrent engineering techniques to complete this project. First, the project team was formed at the end of the spring semester of 2004. After the team was formed, the brainstorming and conceptual design process began during the summer. Since all of the group members attend CSUS, meetings involved face-to-face communication as well as phone conferencing and email updates. Because the project was started early, goals as well as the limitations were set quickly in order to keep on track. One of the limitations this group evaluated was the maximum depth the ROV should travel. This was important because it would add an extra complexity to the project. One of the team goals was to create a hobby sized ROV that could be marketed to key industry consumers. Each of these has played a key factor with the final design as well as cost. Other items that have contributed to the design goals and limitations were industry contacts and online research.

Another key factor to concurrent engineering involves design reviews. Two different groups reviewed this project, Professor Harralson the senior project advisor and Andy Lyons, the industry contact with Schilling robotics. Many trade-offs were made to the design due to the project reviews and cost. First, the original design was larger scale in order to travel 300 feet into the ocean to search and document. This downsizing of scale was necessary due to electronic component cost as well as availability. Second, it was necessary to have an umbilical that was neutrally buoyant. The team opted for making an umbilical instead of outsourcing it, this cut the overall price by 1/3. The last trade-off that was made involved key features to the camera. The original desired camera was a self-contained (water-tight) camera that has the ability to pan as well as tilt. This camera was replaced with an encased camera that only tilts. The compilation of these three items would have raised the cost of the project to over $5000 alone.

When the ROV design was solidified and the appropriate trade-offs completed, the group had to then research components and vendors. The Internet was a very resourceful tool for this aspect because it gave the team the ability to search out the best prices, quality, and variety. This part of the project was tedious but each desired part was located and put into the assembly. With all this accomplished the design team was ready to incorporate Design for Manufacturing, Design for Assembly, and Failure Mode and Effects Analysis.

At the beginning of the 2005 Semester, the project team was able to proceed with the project as well as continuing with concurrent engineering techniques. One of the ways this was accomplished was to break up the manufacturing responsibilities. The ROV frame was submitted to a laser cutting facility, the pressure vessels were made by the CSUS staff, and the project team manufactured the mounting brackets for the motors. The second way concurrent engineering was incorporated was to research and document aspects of the ROV and manufacturing while assembling most of the subassemblies. This allowed the team more time and concentration in writing the final report and documentation for the project.

Market Research and Analysis

The Flying Eyeball was initially designed for exploration and search and salvage missions in deep oceanic terrains. After performing market research for Remotely Operated Vehicles on the market, some possibilities arose for manufacturing and distribution of the Flying Eyeball. The market for this type of Remotely Operated Vehicle is saturated by well funded independent and corporate businesses. It was after conducting this research, the project group made the decision to change our market as well as the scale of our project. The new commercial market for the ROV varies from the hobbyist to video and inspection projects.

There is a vast hobby market that exists today with access ranging from catalogs, the internet, and shopping malls. Due to this vast market, a target group had to be defined to specific enthusiast that would have a strong interest in the product. These types of enthusiast's would include fishermen, boaters and sailors, and curious explorers. The ROV is perfect for each type of enthusiast for distinct reasons. The fisherman would enjoy the ROV to locate and identify fish schools without the noise of the boat disturbing the school. In internet analysis of a radar system versus the ROV, the prices were comparable at a range of $1000 to $1500 for radar. The drawbacks to the radar system consist of portability, the occurrence of the radar output, and lighting and visibility can become an issue. The ROV can be moved from boat to boat, it has independent motion from the boat of up to a 100 foot cord, it can show you in real time what is out there, and the ROV has its own lighting. The boaters and sailors would use the ROV to inspect their investments for leaks and material fatigue. The last type of enthusiast includes boaters as well as shore dwellers that would like to take a look beneath the water without getting in the water. This would allow people that could not get scuba certified or cannot swim to observe the ocean.

Another great use for this unit is Dam surveillance. Dam surveillance is imperative to the life cycle of the Dam because once damage occurs it is a matter of time before the water pressure and deterioration of the material will cause the Dam to break. Right now there are many Dam projects that involve reconstruction because the damage is too extensive to repair and these reconstruction costs range $200,000 to $2 million (reference Stueben Dam, Indiana; Journal Gazette). If Dam facilities have a tool that can catch the beginnings of cracks by performing weekly maintenance, it would save them literally millions in the future. The cost of a ROV per repair facility is approximately $1500; the price investment is a very good compromise to dam failure and million dollar repairs.

The senior project group determined it would be a good idea to survey customers to see how they would react to this innovative device. A survey was compiled and sent out to approximately 30 dive shops*. Four questions were asked on the survey (see a sample questionnaire in Appendix C), how much would you pay, would you rather use a diver or ROV, and provide any feedback regarding the ROV. The result of the survey indicated that dive shops would most likely buy an ROV if it was cost effective with a price range of $3000 to $4000. The respondents also believed that in strict comparison, a diver would fair better in high currents although a ROV would be useful to supervise student divers and to look for lost equipment.

*respondents will not be named or referenced in this report due to confidentiality agreement.

M.A.T.E. Competition

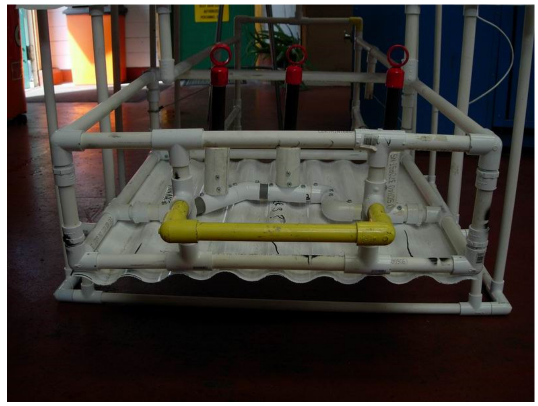
It was decided that the ROV would take part in a M.A.T.E. completion in June 2005. The acronym M.A.T.E. stands for "Marine Advanced Technology Education". The M.A.T.E center is designed to coordinate and help to facilitate ROV competitions that range from regional to national. This project group will compete in the Explorer class "Mission to Europa" competition. This competition is sponsored by NASA and will be held in the Neutral Buoyancy Laboratory at NASA Johnson Space Center in Houston, Texas.

From the M.A.T.E. website, the overview states "The Explorer class is suitable for those who are willing to design and construct an advanced, multi-functional ROV with a sophisticated control and payload system. In addition to the underwater mission tasks, the ROV will be challenged with engineering evaluation interviews, technical reports, and poster displays. The Explorer class underwater competition sends teams on a simulated mission to Europa, one of the six known moons to orbit the planet Jupiter. Europa is significant because it is believed to have an ocean of water beneath its icy surface."

The mission is to simulate the recovery of a space probe that NASA has lost contact while it is submerged under the icy surface of Europa. The ROV is required to:

1) Re-establish the communications link to the science package as illustrated here.

2) Located on a Science package is a sliding drawer made of PVC pipe material. The second mission involves the retrieval of data probes in order to relay the environmental conditions to the base planet.



3) Collect a sample of red fluid from the crevice using an exterior armature.

4) Measure the temperature of the vent venting fluid via an exterior temperature sensor.

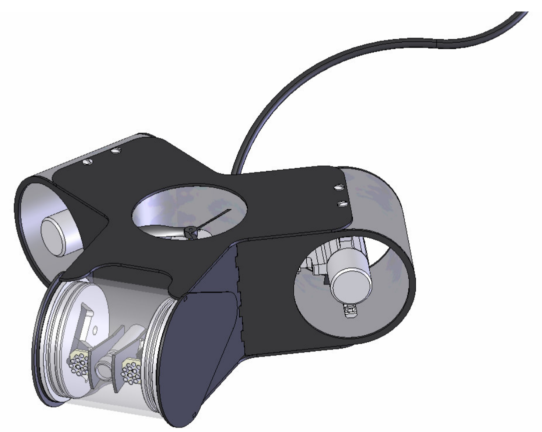
Located to the right is an illustration to the complexity of the Science Package. At first examination, the exterior is a very simplistic design; however the internal design which involves the mission is very complex. On the following page is a sketch of the Explorer class mission setup.

EXPLORER Class Setup

Buoyancy

There are two primary ways for underwater vehicles to ascend or descend in water. The first is by changing their buoyancy and the second is by maintaining neutral buoyancy at all depths and using a thruster to move up and down in the water. Large submarines primarily use a system of bellows, which they blow up with air within the hull to increase buoyancy causing them to surface and then releasing those bellows to dive again. This configuration is used by large subs because it allows for a large range of loads. Utilizing bellows as the main buoyancy allows for the use of one main thruster or "screw" for forward motion. Also, it is possible for front bellows to be inflated in opposition of the rear which angles the ship upward or down allowing the main thruster to help dive or surface.

For smaller underwater vehicles the problem of varying weight usually does not pose a problem because they do not make daily changes to their buoyancy configuration. This is especially true for "Eyeball" class robots which normally only have a camera for the primary load. The buoyancy of these smaller robots can be reconfigured for multiple tasks by having more buoyant material than needed and adding weight to particular areas of the frame as a placeholder for parts added later.



Buoyancy is a driving factor behind any ROV's design. If the vehicle is too positively buoyant it will reduce or completely counteract the robots ability to dive. The reverse situation of having a robot that is too negatively buoyant is more of a pressing problem. If the buoyancy issue is not properly addressed, this project might as well be a camera attached to a rock.

It is because of this importance that great care was taken in designing a balanced, neutrally buoyant ROV, which will only require one thruster for control of depth as can be seen in the "Porpoising" section. This was desirable because the flying eyeball was not only designed for educational purposes but for competitions as well, specifically the MATE competition. This competition requires the performance of approximately 2-5 predetermined tasks; it is because of this that the vehicle in design will be positively buoyant by 0.75 pounds and brought to neutral buoyancy by weights.

The buoyancy was designed to be the one dynamic feature that can be used to compensate for any additional peripheral objects such as grabbers or instruments. By removing dense lead weights from within the frame and replacing them with peripheral objects approximately the same weight in water, it is possible to maintain neutral buoyancy while having a reconfiguration option. After deciding the best configuration for the buoyancy, it was then imperative to choose the best type of material and check the initial assumptions against actual calculations.

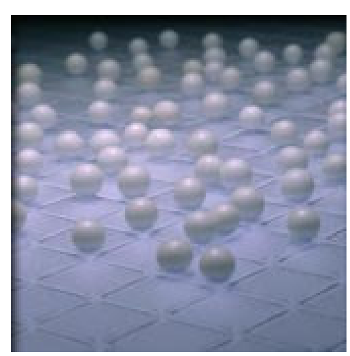
Choosing Material for Added Buoyancy

As can be seen in the "Porpoising" section this robot was designed to have a symmetric frame for reasons of drag. The design challenge comes in allocating space within the confines of the closed frame and finding a buoyant material which packs the greatest buoyant punch possible to reduce overall volume of the frame. This material must be strong enough to withstand the pressures of operating 150 feet under water without being so heavy it counteracts its function of adding buoyancy; this is a tall order. Styrofoam was the first material considered because of its compressive yield strength, low density, and low water absorption. Figure 1 shows this material being used for flotation on a dock. This use shows that the material is effective at supporting large loads while submerged for long periods of time without loosing effective buoyancy. Styrofoam is cheap and readily available in large sizes via Internet purchase. Although Styrofoam was the initial choice for the flotation, the final decision for flotation was syntactic foam

Figure 1

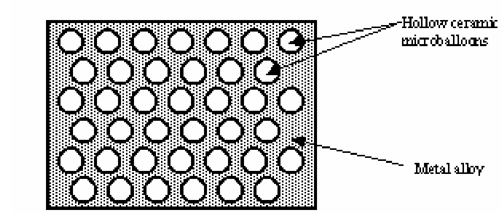
Syntactic Foam

Syntactic foam is a designer foam that is composed of tiny, hollow spheres, called micro-balloons, and a resin. The hollow spheres are made of glass and the most



widely used resin is epoxy. To make this foam the spheres are mixed into a binding resin, then a curing agent and other additives are added to the mix, creating a fluid mass that is later made into foam. This foam is not like typical foams.

Typical foams are made by mixing or injecting a gas into a liquid, creating froth. The froth then solidifies and creates the foam. In Syntactic foams, the froth is "prefabricated," bubbles are manufactured and then combined with the resin to form the composite material. This combination allows for a low density composite with high compressive strength.



Low-cost, syntactic buoyancy foam called AM-28 was donated to this project and is used as our floatation. AM-28 has a depth rating of 3,300 feet, a compressive strength of 3,380 psi, and a density of 28 lbs/ft^3. This foam is convenient because it is easily machined using typical wood working tools. These specifications more than meet our specifications for the project and makes AM-28 foam the primary choice. Once the foam is cut to the drawing specifications it is then inserted into specially designed areas inside of the ROV and attached to the top of the ROV as seen in the Buoyancy Document.

Pressure Analysis

When materials are submerged to 100 ft of water the pressure can be so great that it reduces the materials volume, reducing its effective buoyancy.

The "specific weight" of salt water is less than that of freshwater, and can be seen above compared to 62.4 lbf/ft^3 at 50°F. When the specific weight is multiplied by 100 ft it gives a pressure of 43.0 psi (calculations in Appendix B). Since the Syntactic foam has a depth rating of 3,300 ft and compression strength of 3,800 psi, this gives the ROV a large safety factor. With this in mind, the team will not have to focus on any failure due to the compressibility of the flotation**.**

Buoyancy Configuration

Calculating the overall buoyancy is very important for making this vehicle neutrally buoyant but it is only half the challenge. There must be the correct amount of buoyancy in the correct configuration, which plays a huge role in determining the stability of the underwater vehicle. There are two axes of rotation, pitch and roll, where buoyant and gravity forces imposed on the vehicle must cancel to be stable, as can be seen in Figure 3. If these forces do not cancel the vehicle will sit awkwardly in the water as is shown in the "Porpoising" section.

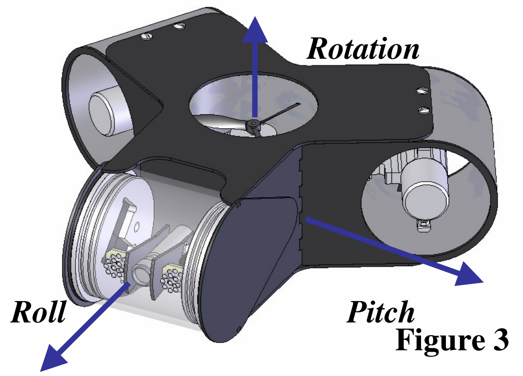


Figure 3

Table 2 was the first analysis of the ROV, with buoyancy in a "best guess" configuration. The table below shows the force distribution or "F_d" which is the sum of the net force of each section taking into account added buoyancy. It can be seen that the buoyant forces for the "Roll" axis (sections **B** and **C)** will cancel out because of symmetry as can be seen in Figure 4. Using this table, problems can be seen with this initial configuration for the "Pitch" axis. Section **A** is more than a pound and one half more buoyant than the adjoining **B** and **C** sections respectively; this is from buoyancy created by the camera bay pressure vessel. Also it can be seen that the total buoyancy is more than 1 ½ pounds negative.

Table 2

	Wg (lb)	Vp (in^3)	Fb (lb)	Fnet (lb)	Fd (lb)	Section
Camera Bay:	4.37	60.73	4.77	0.40		
Added Front Buoyancy:	0.03	20.76	0.75	0.72	1.12	A
Right Thruster:	2.69	38.47	1.39	-1.30		
Added Right Buoyancy:	0.03	22.36	0.81	0.78	-0.53	B
Left Thruster:	2.69	38.47	1.39	-1.30		
Added Left Buoyancy:	0.03	22.36	0.81	0.78	-0.53	C
Center Thruster:	2.70	38.66	1.40	-1.30	-1.30	D
Symetric Frame:	1.86	50.56	1.83	-0.04	-0.04	
Total:	**14.41**	**292.37**	**13.13**	**-1.27**	**-1.27**	

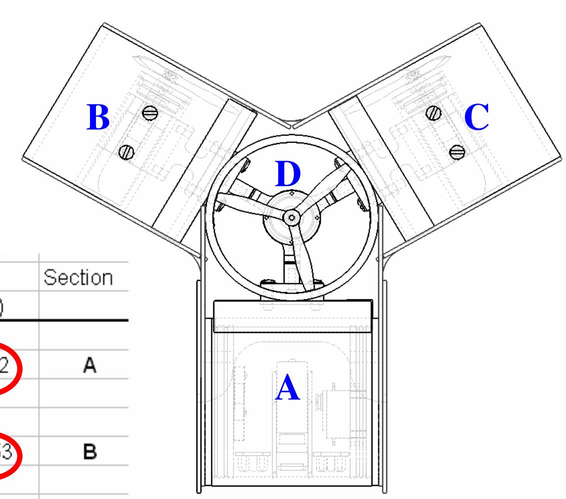


Figure 4

These initial findings constituted a large change in buoyant material volume and configuration. Previously buoyant material was mounted near the top half of the interior frame, this helps to overcome porpoising back and forth along the "Roll" axis when in rough water. This added stability was sacrificed for the needs of extra buoyancy as a design tradeoff, so buoyancy was added to the bottom half of the interior frame. In addition the design was changed again to have more available space inside the frame by lengthening all three outer sections away from the center and wrapping the buoyant material around into previously unused areas. This was the best solution for overall balancing and maintaining the correct buoyancy configuration while only extending the sections out one more inch.

Table 3

	Wg (lb)	Vp (in^3)	Fb (lb)	Fnet (lb)	Fd (lb)	Section
Camera Bay:	4.37	60.73	4.77	0.40		
Added Front Buoyancy:	0.03	20.76	0.75	0.72	1.12	A
Added Front Weight:						
Right Thruster:	2.69	38.47	1.39	-1.30		
Added Right Buoyancy:	0.06	51.48	1.86	1.79	0.49	B
Left Thruster:	2.69	38.47	1.39	-1.30		
Added Left Buoyancy:	0.06	51.48	1.86	1.79	0.49	C
Center Thruster:	2.70	38.66	1.40	-1.30	-1.30	D
Symetric Frame:	1.86	50.56	1.83	-0.04	-0.04	
Total:	**14.48**	**350.62**	**15.24**	**0.76**	**0.76**	

Table 4

	Wg (lb)	Vp (in^3)	Fb (lb)	Fnet (lb)	Fd (lb)	Section
Camera Bay:	4.37	60.73	4.77	0.40		
Added Front Buoyancy:	0.03	20.76	0.75	0.72		A
Added Front Weight:	0.69	1.62	0.06	-0.63	0.49	
Right Thruster:	2.69	38.47	1.39	-1.30		
Added Right Buoyancy:	0.06	51.48	1.86	1.79	0.49	B
Left Thruster:	2.69	38.47	1.39	-1.30		
Added Left Buoyancy:	0.06	51.48	1.86	1.79	0.49	C
Center Thruster:	2.70	38.66	1.40	-1.30		D
Added Center Weight:	0.10	0.24	0.01	-0.09	-1.40	
ABS Frame	1.88	50.56	1.83	-0.05	-0.05	
Total:	**15.28**	**352.48**	**15.31**	**0.03**	**0.03**	

After these design adjustments it can be shown on Table 3 that the total net buoyancy became 0.76 lbs. The force distribution for the rear thrusters is approximately a half-pound each and the front camera bay is a more than a pound. For the robot to sit level in the water, sections **A**, **B**, and **C** must have equal buoyant forces while still collectively canceling out the weight of the center thruster section **D** of 1.3 lbs as can be seen in Figure 4. It was a pleasant surprise to find the ABS sheets to be nearly neutrally buoyant as can be seen on Table 4 under "ABS Frame". This that means no mater how the ABS frame design is altered the overall buoyancy and, more importantly, the buoyancy configuration will not change.

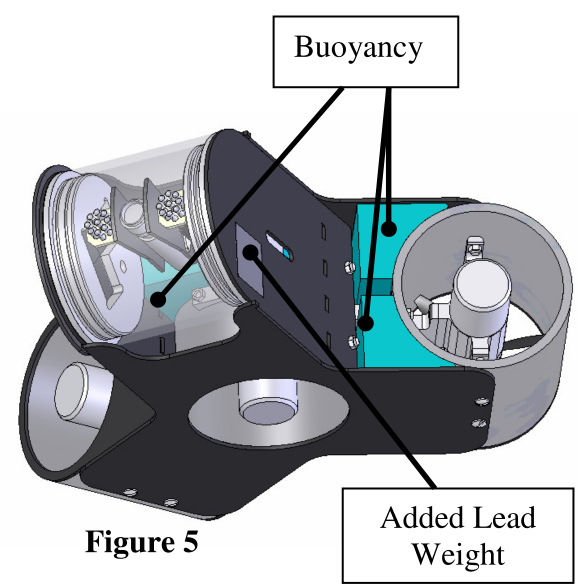


Figure 5

The overall 0.76 lbs buoyant force was counteracted by adding dead-weight to the frame which was a good thing because it could be put just about anywhere because of how small the volume of a dense material like Lead could be to drop the buoyancy by less than a pound.

Approximately 0.63 lbs was added to section **A** to give a distribution force approximately the same as sections **B** and **C**, ***(1.12 lb - 0.63 lb) = 0.49 lbs*** and the remainder of the needed weight ***(0.76 - 0.63) = 0.13 lbs*** will be added to the center section. All of this dead-weight will be mounted as low in the frame as possible for stability reasons mentioned above. The result is a stable neutrally and symmetrically buoyant ROV.

<u>Porpoising</u> Porpoising is the undesired role, rotation, or directional movement caused by propulsion and can also be defined as undesired cyclical motion of a stationary vehicle. Porpoising can be caused by any one of several underwater conditions, such as unbalanced buoyancy, miss configuration of buoyancy, non-symmetric thrust forces and non-symmetric drag forces. An underwater vehicle can be considered a free body unconstrained by any axis and is affected by forces of buoyancy, thrust and drag. It is a complex exercise of balance and symmetry to produce a viable three thruster neutrally buoyant ROV design. Some underwater vehicles use buoyant porpoising intentionally to tip the vehicle down or up to get better thrust properties when diving or submerging (See Buoyancy Section). On a neutrally buoyant, three thruster vehicle this is not always the case. It is desirable to be perfectly horizontal in the water so that when the horizontal thrusters are used, the vehicle only moves horizontally in the water. If this alignment

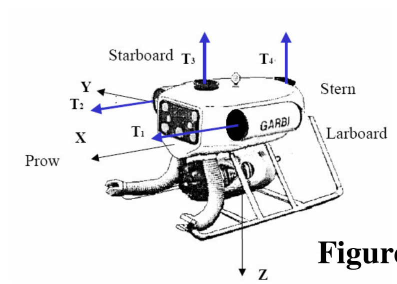


Figure 2

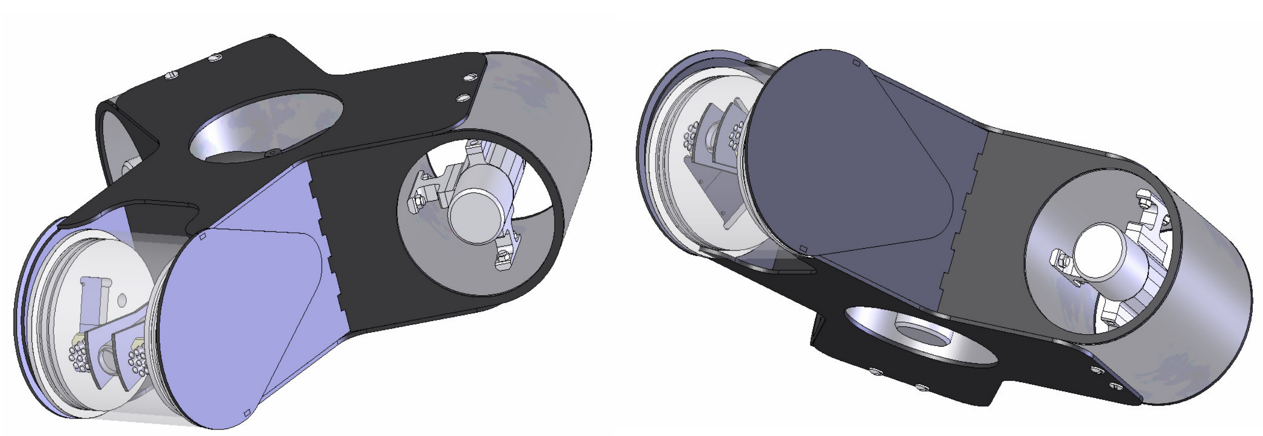


Figure 1

is not correct the vehicle will always dive or submerge every time the horizontal thrusters are used whether this action is desired or not.

Porpoising can also be caused by non-symmetric thruster forces where the thruster forces are not applied to the center of mass taking into account other drag forces. It is possible to correct this by adding more thrusters so the operator has a greater ability to correct the porpoising as it happens. This can be seen when considering other vertical thruster configurations of neutrally buoyant ROV's in today's market which usually have two thrusters, front and stern, such as the configuration above taken from an ROV from the university of Girona named "Garbi". These added thrusters give the operator more power when submerging or surfacing, but costs more and requires a longer frame.

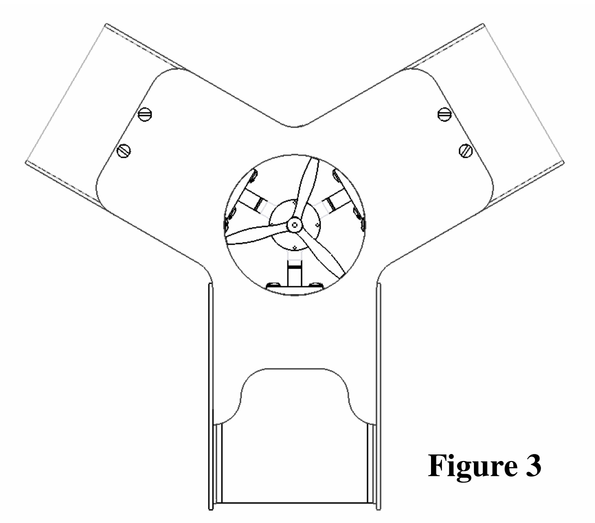


Figure 3

A single thruster system is less expensive but reduces control of the pitch on the Y axis. If the buoyancy configuration is not correct it will cause the vehicle to submerge at an angle perpendicular to the surface, missing the desired target, but this configuration is not impossible. This same problem can be created by non-symmetric drag forces when submerging. An example of this is if the frame has a greater drag force in the rear than the front when submerging it will cause the vehicle to tip its nose downward. This won't allow the vehicle to go straight down to the desired target.

This Senior Project Group decided to create a neutrally buoyant, three thruster ROV using a single vertical thruster as can be seen above. This design is at first glance very simple but in reality requires complex calculating to find correct arrangement of buoyancy while maintaining particular frame configuration. The vertical thruster was set directly in the center of the ROV so it wouldn't porpoise when submerging or surfacing. A two

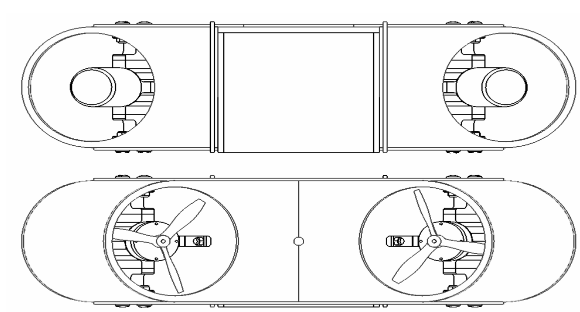


Figure 4

thruster configuration was considered for our design for the positive qualities addressed above, but that took up too much space along the length of the frame, making it too long. It was agreed that if the need should arise for having more vertical thrust this group would simply increase the power of the single vertical thruster. The thruster housings and front camera bay are set at 120° from each other giving a symmetric configuration which will be acted upon by friction equally as the vehicle submerges, as can be seen in Figure 3. The same goal was achieved along the horizontal axis as can be seen in Figure 4 where the force of thrust from the motors is set along the horizontal center plane of the body. Also you can see that the umbilical will

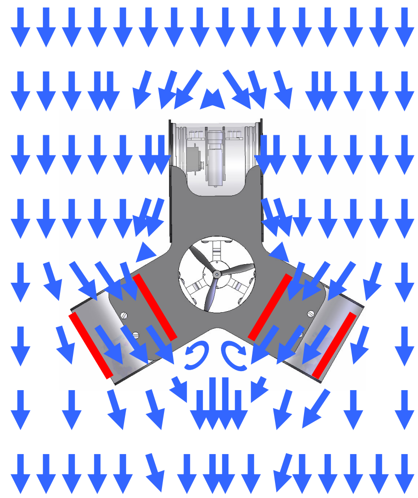


Figure 5

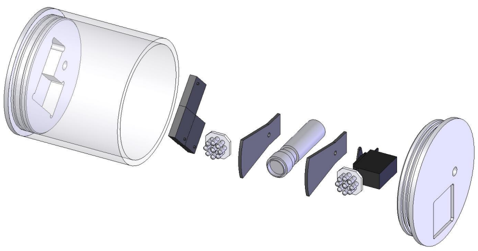
enter through a hole in the frame along that same plane. Because the horizontal thrusters are 30° from the flow of water, shown in red in Figure 5, the efficiency will be reduced. This is a design trade-off for reduced vertical porpoising when the ROV is submerging or surfacing. Because of this thruster configuration the water flow will be concentrated at the rear creating turbulence directly behind the vehicle, as can be seen in Figure 5.

Camera Bay Assembly

The camera bay located on the front of the ROV contains all of the electrical components and camera, making it a pressure vessel. The material chosen for the bay was an acrylic cylinder 5 ½" in diameter and ¼ " thick wall. Acrylic was an ideal material because it is cost effective, transparent, and will not set at 150 feet. Acrylic has a tendency to set or deform when left under pressures for any length of time. It is not critical while the vessel is submerged but when the ROV begins to ascend, the stress caused by the acrylic trying to regain its natural set causes it to crack and fail. The time and degree of the set depends on the wall thickness of the acrylic, an analysis performed by Jon Nellis with Schilling Robotics found that an acrylic cylinder with a wall thickness of ¼" and a depth of 150 feet, will not set.

The camera bay will be sealed by two Aluminum 6061 caps that will then have ABS sheets mounted to the top. These caps will have two grooves machined into the sides to insert two O-rings. These O-rings are instrumental for keeping the bay watertight. The O-rings used will protrude slightly from the grooves so that upon assembly they will compress and create the watertight seal as well as an interference fit between the Aluminum cap and the acrylic cylinder.

Located inside the cylinder are the key electrical components for the ROV, three motor controllers, a receiver, two LED light clusters, and the digital camera. The motor controllers are marine based and were chosen because they were water resistant, small in size, compatible with the motors, and can switch between the forward and reverse



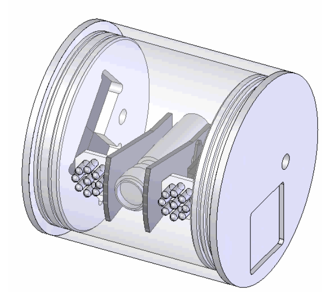
directions with minimal hesitation. The LED lights were chosen because they were small in size, generate minimal heat, and they are easily serviced when they burn out. The receiver is a simple remote control six channel car receiver that will help control the ROV. The receiver was chosen for its size as well as it versatility for our project. The camera was an important piece for the project and it is discussed in detail in the following sections.

Once the electrical components were sealed in the camera bay a way to get the cords out of the bay and to the surface had to be found. This will be done by using an A.N fitting or penetrator. The A. N fitting is an L shape hollow tube with threading and tube barbs on one side. It will be inserted through a machined hole and then sealed on the bay side with an epoxy and tightened to the outer side with a nut on the threads. Anything that penetrates our pressure cylinder causes a Failure Mode in the ROV. To ensure that this fitting will not cause a critical failure, the part will be inspected before assembly and the machine shop will machine the fitted hole to ensure proper tolerances.

Camera

Design Criteria

Our design criteria consists of the following features; the camera case may not have any measurable water leakage, it needs to have a variable focusing lens, have a digital signal with an output resolution line range of 380 to 400, and have a lux rating from .5 to 2.0.



Design Logic

The features listed above were essential to our design due to the harsh underwater environment. The first design criterion involving the permissibility of fluids into the camera case is necessary for two reasons. The first need for a watertight case is due to video quality. If water were to enter near the lens of the camera, the quality of the video is impaired. The second need for a water resistant camera stems from the possibility of critical failure. If too much water enters the casing of the camera, the electronics will short and the camera may be damaged.

The next desired feature, a variable focusing camera, is favorable because of distortion caused by underwater object distance in reference to the ROV as well as possible distortion from the acrylic housing**.** The ROV camera will operate similar to a human eye. For example, the human eye is focused according to distance from an object as well as lighting. In addition to distance and lighting, the ROV will also have to focus on objects that are moving at different rates and directions to its self, this variable focal feature compensates for this and provides good quality video feedback.

In order to view and record the video footage from the camera, the camera needs to have a digital output with a resolution line range of 380 to 480 as well as record in low lighting. A digital signal will allow the images sent from the video to be viewed by a laptop or a Television and then recorded by the laptop or a VCR. A typical VCR registers only 240 lines of resolution and once objects are recorded onto a VCR tape they tend to be blurred. This can be resolved by using a camera with higher resolution lines and more pixels**.** More pixels means better focal quality if you start with a higher resolution and clearer picture. Once an image is captured by the camera, it is then recorded onto a VCR tape, depending on the depth of modulation a blurring will occur.

Typically cameras with a resolution of 400 lines as compared to 240 lines will have less incidence of blurring and the output is better. A normal laptop contains 768 lines of resolution, so it was necessary to have a camera that would translate a high quality video across a laptop without appearing blurry. The last feature the camera needed was a low lux rating. The term lux is used to define how much light something produces, however, a lux rating for a camera refers to how sensitive the camera's CCD (chip shutter) is to receive light. A rating between .5 and 1.5 is best for the lighting scheme underwater.

With this criterion in mind, it seemed practical to buy a completely waterproof camera that would be attached to the exterior of the ROV body. This idea was not practical because the cost of an underwater camera ranged from $500.00 to $985.00

depending on the inclusive features. Not only was the camera expensive, but this design would require a waterproof servo that cost approximately $3000.00 for pan and title features.

Camera Choice

The camera that was chosen for the ROV is a variable focus bullet camera. This camera is not waterproof so it will be contained in a watertight pressure vessel. It has 380 resolution lines and is comparable to other cameras on the market. The shutter speed translates 1 frame for every 1/60 of a second which is the NTSC (National Television Standards Committee) standard and has a .5 lux rating.

Transmission from the camera to the laptop was an important function to the project. If the picture sent from the camera cannot be viewed on a laptop, then the only option for viewing is a type of portable TV screen. The device used to convert the video signal from the camera to the laptop is called a Codec. This device takes the analog signal and converts it to digital so the laptop can then interpret it. Computer video software will then record the images displayed by the laptop.

Camera Specification Sheet

Model KPC-S230CV	
Signal Format	NTSC
Total Pixels	537H x 505V
Effective Pixels	510H x 492V
Horizontal Resolution	380 TV Lines
Electronic Shutter	1/60-1/100,00 sec
Signal Process	Digital
Sensitivity	.1 Lux
Power Supply	DC 12V
Operating Temperature	10 degrees below 0C and 50 degrees above 0C

Umbilical

Desired Features

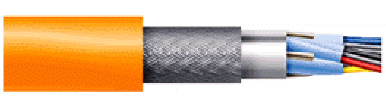
The desired features for the umbilical cord consist of the following; reduce the amount of drag by having a minimum diameter, provide the ability to transmit power as well as send digital signal in one combined jacket, neutrally buoyant, no less than 250 feet of tether, and be cost efficient.

Design Logic

In order for the ROV to move efficiently through the water, the amount of total drag needs to be as low as possible. Since the vehicle is underwater, the body will create a set amount of drag. Since this drag is inevitable, it can only be reduced by structural redesign, which will only reduce it not eliminate it. This created the need to eliminate drag anywhere else possible. One of the ways to reduce the drag was to find a cord with as small diameter as possible. There are various designs and ways to reduce the diameter of an umbilical cord. The most common way to reduce diameter is to die extrude the necessary cord. Die extrusion is the process of taking material and pulling or extruding it through a specially manufactured mold. The die extrusion process removes the air pockets between the inner wires as well as compressing the wires together in a fitted jacket. The process for the umbilical also incorporates a calculated amount of buoyant material internally that makes the wires neutrally buoyant. This process is expensive because the demand for this product is low as well as the high cost of the extrusion die.

A second way to reduce the diameter is to buy a cord with the minimal amount of gage wire. Since wires come in various gages, this is a more inexpensive way to go. The last alternative to reduce the diameter of the cord is to reduce the number of wires needed in the umbilical. Although many ROV's on the market have additional peripheral devices that require more power as well as additional wires, the Flying Eyeball only needs power for the camera, the LED lights, motor controllers and the motors. This allowed for a wider range of cables, such as a RG59 cable and a separate power cord that can run to a splitter and then run to the peripheral device or a Siamese cable. The Siamese cable is a combination of a RG59 cable and a power line combined in one case. These types of cords are more inexpensive than having a special umbilical cord made.

Another important aspect in choosing an umbilical is the buoyancy factor. The buoyancy of the cord is an additional barrier to the amount of total drag. This issue became a very difficult problem for the ROV. There are two ways to reduce the buoyancy in the cord, buying a neutral buoyant cord or adding or removing buoyant force to the cord. Adding floats to the cord by fastening them strategically throughout the cord can make it neutrally buoyant or adding weights if the cord is positively buoyant.



The last two desired features require the cord length to be no less than 150 feet and to be affordable. For the design specification of an ROV for a depth of 100 feet it is necessary to have additional cord in case of possible snags as well as the necessity to explore laterally once at the 150 foot depth. Lastly, the issue of cost for the cord can be a factor on consumer cost as well as the overall manufacturing cost. One way to affect the cost of the cord is to buy a coaxial cable instead of special ordering an extruded umbilical cord. The other possibility to reduce the cost of the cord is to make the cord neutrally buoyant instead of buying it from a company who specializes in making a buoyant cord.

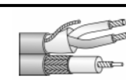
Umbilical Choices

The type of umbilical the ROV will utilize is a RG59 Siamese Coaxial cable. A coaxial cable is an electrical cable consisting of a conducting inner wire or

wires surrounded by an insulating spacer and covered by an outer sheath. This type of cable is designed to carry high frequencies, broadband signal and sometimes power. This cable was chosen for a variety of reasons. Cost was the biggest reason for choosing this cord, as explained; an umbilical tailored for this project could cost as much as $2000. A secondary reason for this cable is the combination of the power, the digital signal feed, and instrumentation cable in one jacketed cord. This allows power to be sent down to the peripherals as well as send the digital signal back to the surface. The additional wires in the cable are necessary so we can attach additional instrumentation and the remote control for the steering.

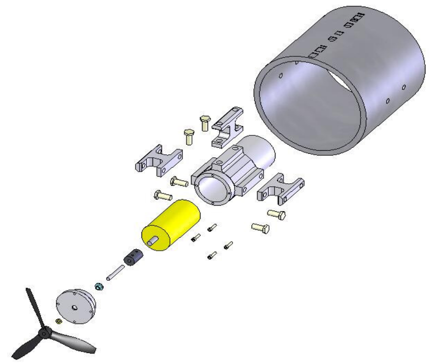
The one drawback to using this cable is that it needed to be altered for buoyancy. Since a method for computing the absolute placement of buoyant material on a cord is nearly impossible, the task was accomplished by iteration. Styrofoam floaters were purchased from a fisherman's store and the placed strategically on the cord. This process was repeated several times until neutral buoyancy was reached.

Specification Table for Umbilical

Belden Part No. 9265	
Signal Format	Digital
Impedance	75 Ohms
Max. Voltage	300V
Shielding	95% Bare Copper Braid
Amperage 18 gage wire	18 AMP
Outer Diameter	.242 inches
Dielectric	BeldFoil
Temperature Rating	below 70C and above 200C
Application	Outdoor Usage

The ROV Thruster system

Desired Features



The desired features of the thruster system consist of the following; adequate power supplies for the motors, combinations of motor and propeller that will counteract drag forces at a speed above 0.2 m/s, and motor controllers capable of handling the current flowing into a locked shaft motor.

Design Logic

The power source for this ROV is DC because the electric motors and controllers will only accept DC current. In order to use AC outlets and generators, it is necessary to use a DC converter, which will be placed outside the ROV and DC will be sent down the line. If AC is not an option then DC can be obtained from a 12V battery and sent straight down the line without a need for a converter. The motor controllers are easily capable of handling the current the AC outlet will be sending to them, which will be 2 amps when the drive shaft is locked. However, since the depth rating is only 100 feet, it is more plausible to use a battery and send DC down the line than use AC.

After establishing a power scheme, the specific thruster components were selected. The best motor controllers for this job were a marine based boat motor controller. The nice features of these motor controllers are that they are water resistant and capable of forward and reverse motion without a severe time delay. The water resistance is a nice just-in-case-something-leaks feature but does not allow the controller to stand alone against water. The reversibility feature of the motor controller is really nice because it minimizes the time required to go from forward to reverse, whereas other motor controllers assume that inertial forces will cause gear failure if switched to full reverse. Aquatic propulsion does not require this kind of safety measure, and is actually hindered by it.

It was decided that using a Planetary Gear Motor that is geared 19:1 should be the initial design criteria for the robot, because of its size and power. To match this motor to a propeller, it is necessary to compare the speed v. torque curves of both components to get an accurate assessment of expected

performance. To do this, the no load rotational speed and the locked torque of the motor must be known. In the initial case, these values are 263 RPM at no load and 0.7966843 Nm with a locked shaft.

In order to calculate the propeller curve, the equation

$$T=CN\rho r^3_0\omega^2D^2$$

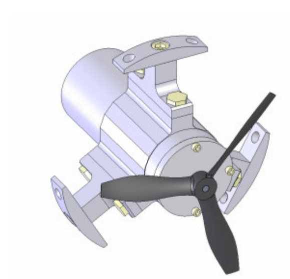
may be used. The problem with this is that C is a constant based on the design of the propeller, and is codependent with the drag on the vehicle, which is based on the speed. What can then be done is to use charts in a book (*Engineering fluid mechanics* by Clayton T. Crowe, Don F. Elger, John A. Roberson) and figure out an estimated value for these constants.

For drag forces caused by the robot's geometry, the equation $F_D = C_D A_p \rho V^2_0/2$ can be applied. **Observing figure 11.11 and Table 11.1,** assumptions were made to obtain an estimation of key forces, which were to assume a velocity 2.2352 m/sec at a d value of 0.1524 m, which gives a Reynolds number of 2×10^5. Given the chart data taken from the fluid mechanics book, a reasonable constant of drag was assumed to be between a disk and hemisphere, giving a value of $C_D = 0.6$. Assuming an area of 0.4572m x 0.1524m = 0.06967728 m², F_D = 25 Kg m/s². Since maximum speed occurs at $F_D = F_T$, calculations are performed by equating drag to the force of the propeller as follows.

$$F_T = C_T \rho n^2 D^4$$

The Coefficient of thrust is a function of the Velocity divided by the diameter and rpm of the propeller. The curves developed for this coefficient are based solely on the propeller design itself, but for the propeller a generic curve was used because they were group designed. The resulting top speed calculated for this robot is 0.2 m/sec.

These equations are subject to many forms of error. The first and most glaring is the lack of a curve specifically for the propeller that we are using. The second and perhaps equal problem is an accurate drag coefficient curve for the robot itself. Given these things, the torque to speed curve would better reflect the capacity of the motor to drive the propeller though the water.



The solution then to this problem is testing each component and its compatibility with the others. The propeller curve can be derived from a water tunnel test, with points taken at speeds appropriate for the project. The drag curve can be roughly gained from a simple test of dragging the robot through a swimming pool. The latter should be performed, but the first may be difficult given the resources at hand. Of course, the most telling experiment will be the actual observed speed of the robot, but these equations and tests allow for adjustments to be intelligently selected.

<u>Seal Selection</u>

Desired Features

O-rings that will have a low compressibility factor so that when under pressure, it will experience minimal distortion. This is imperative because the O-rings fit into tight tolerance glands and need to deform just enough to seal the gap and prevent leakage.

Design Logic

Selecting the seals themselves for the pressurized vessels is a very simple procedure. The first step is to select the material for the seal. There are many types of different materials for different uses ranging from metal to rubber. After selecting the material it is then necessary to decide on the size the vessel will need according to the machined gland sizes. The major gland equations are located in Appendix B. From these equations, a matching gland and O-ring can be selected to the dimensional specifications. Once the pressure vessels are sealed it is then necessary to locate an appropriate dynamic rotational seal for the protruding motor shaft. The best seal for this part is the PTFE dynamic seal.

The spring-loaded PTFE seals function in the same manner as an O-ring in its basic principle; however these seals are engineered to maintain a seal in rotation and in spite of wear. These seals are matched with a shaft of the specified diameter and a gland with the specified outer diameter. The shaft size is bigger than the seal inner diameter to seal the shaft. This seal will be pressed fit into a designated groove on the exterior of the motor vessel cap.

The U shaped is designed to cause a seal under pressure by deforming against the gland it sits in by the pressure inside pressing outward. This allows a shaft to rotate and the seal to maintain constant sealing at the same time. Spring loading the inside of the PTFE aids sealing when not under pressure and when wear causes discrepancies in the seal itself. It is desirable to use the graphite-reinforced seal because the shaft will be spinning at high speeds and wear is reduced significantly with graphite reinforcement.

Design For Serviceability (DFS)

One of the goals of any project is to maintain a design that must be possible to assemble, and that as a secondary concern should be quick to assemble or disassemble should anything need repaired or replaced. The remotely operated vehicle has been designed to take this into consideration. It incorporates many design characteristics that enhance the speed and ease with which a pair of individuals can assemble and disassemble our robot. Simplicity is the key attribute for serviceability and is explained in the following paragraphs.

The foremost serviceability feature is the simplification of the frame. The frame itself provides the various subassemblies to be firmly attached together, while allowing them all to become independent with the removal of a few bolts. The assembly and disassembly of the robot is best performed with two people to allow one to hold the robot components and the other to turn the wrench, but it could probably be performed by a single dexterous individual who is determined enough. With the frame apart, what remains is the main acrylic pressure vessel, the three motor assemblies, the buoyancy packages, and the robotic wiring connecting all of them together.

Unbolting the main acrylic pressure vessel reveals all of the camera components, allowing for detachment of the electronics and freeing the pressure vessel. The camera, its LED lighting, servos and guards are all placed linearly in a shish-kabob fashion. This setup allows the user to disassemble the juicy innards of the camera bay away from acrylic case.

The motor pressure vessel assembly goes together very easily. The motor mounting brackets are attached with bolts. The pressure vessel is also held together with bolts, and the two halves come apart easily. Our shaft must be removed along with the end cap, complicating the assembly and disassembly of the motor vessel, but this is tolerable and in reality can not be helped. Once that occurs, the motor can be removed and the wiring detached to replace or repair the motor itself.

The wiring runs though the robot in a two dimensional fashion, which allows the wiring to be removed and reinserted with a minimum of difficulty. The umbilical is held by a clamped bracket at the rear of the robot.

Serviceability is especially important in our project, since a number of our sealing components, such as the mechanical seals around the propeller shaft will need to be replaced from time to time. As always, the longer a product lives, the higher the probability of component failure. This product is expected to have the ability to continually replace any fouled components to potentially extend the lifetime of the product.

Design for Manufacturability (DFM)

The critical criteria that govern the cost of any product are the manufacturing techniques that are used. The proper consideration of how a part is going to be cast, cut or machined and then assembled can make the difference between a product that is going to sell at a profit and one that is going to lose money even if it sells well. This project made certain to limit and standardize the processes that will be used in manufacturing the ROV.

The frame is a key component. The design was developed to make use of laser cutting techniques by developing a frame composed of two dimensional plates. The frame was then designed to take advantage of one eighth inch ABS sheeting, which could be laser cut to our exact dimensions. This frame is perfect for the complex, low volume parts we will need for our frame, and is in fact very inexpensive compared to other techniques. For permanent part mating, glues that melt the plastic can be employed, essentially "welding" sheets together. This is far less expensive than the original design that involved welding aluminum bars.

The motor pressure vessel assembly incorporates a motor mounting system that would have been incredibly difficult to manufacture from a single piece. However, with additional design that took into account the manufacturability of the part, the motor mount was split into three distinct and easily manufactured parts. These parts will be machined from plate aluminum, and the additional effort saved an enormous amount of time that would have been used in manufacturing.

While unique components are necessary, we aimed to use readily available parts to simplify and standardize the design. The motor shaft tubing and acrylic pressure vessel tubing are going to be cut from standard extruded forms that will significantly reduce the cost of the ROV. If these parts were not standard, they would require extremely expensive services to manufacture.

Components that were originally designed to require welding have been eliminated, and the use of multiple metals that would have introduced dielectric corrosion effects has been simplified to only utilize aluminum. Because the bolts on our ROV would have required isolation if they were had been stainless steel, we have significantly reduced the manufacturing cost for our robot by switching to less well known nylon bolts.

The manufacturability of this ROV has been a primary concern. Thus, the manufacturing techniques and processes have been standardized across the robot. Attention to the manufacturing costs associated with each component has dramatically reduced the price tag of our robot when compared to the original.

Manufacturing Process

The manufacturing for the ROV was very complex due to the intricacies of the multiple pressure vessels as well as the connectors that assemble the individual pieces together. The pressure vessels consist of the motor housings and the camera bay. Both of these pieces are critical and will lead to failure if they are not manufactured accurately. Since the two components in themselves are complicated, they will be discussed separately. The main machinery used to fabricate our pieces includes the Computer Numeric Control machine (CNC), vertical mill, and lathe.

The camera bay was the first piece that was manufactured. It houses not only the camera, but all of the electrical equipment, and was the single assembly that took the longest to fabricate. The camera bay consists of an acrylic tube, two aluminum caps, and a laser cut mounting piece for the camera. The mounting piece for the camera is a part of the laser cutting manufacturing and will be discussed as a separate process. The acrylic tube was pre-cut by the vendor that sold it and was not an issue in manufacturing. The aluminum caps, however, were very intricate and took three weeks of preparation before it could even be put on the CNC machine. The caps had to be converted from a two dimensional drawing to a three dimensional drawing before it could get converted into code for the CNC. Once the drawings and codes were completed, a slab of rectangular aluminum was mounted into the CNC and slowly whittled away. The first cut consists of cutting the slab into two pieces as well as sizing the exterior diameter of both of the caps. Once this was successfully completed, the CNC was then programmed to make all the interior cuts as well as countersinking the mounting holes on the exterior of the caps. Since none of the members of the ROV team have the necessary skills to run the CNC machine, Jim Stir fabricated this part.

The second piece that was manufactured was the motor assemblies which we needed a quantity of three. The motor assembly is comprised of the motor, the motor pressure vessel, the motor housing, the mounting brackets, and the propellers. The motor was purchased from a vendor and dimensioned in order to fabricate the pressure vessel. The pressure vessel consists of two pieces made of aluminum, the cap and body. These two pieces were machined initially on the CNC as separate pieces and once the machine was set up for the first housing, the other two were easily completed. After they were machined on the CNC, the body was then put on the vertical mill to bore out the interior as well as drill holes for the screws that will seal the vessel. The cap was also placed on the vertical mill in order to cut the grooves for the O-rings and dynamic seals and drill the screw holes.

The mounting brackets for the motors are also manufactured from 6061 aluminum. The first step in making the brackets was to cut a generic size for each of them because the 6061 aluminum was purchased as a rectangular bar. After the bar was cut using a ban saw, they were then placed on the vertical mill. This enabled a team member to size the bracket according to the specified tight tolerances. After sizing the brackets, they were then drilled and then taken to Jim Stir to finish the radii cuts that allow the brackets to sit in the circular motor housing.

The propellers were not machined but specially sculpted for this project to get maximum output and it was a very involved process. The prototype was sculpted using modeling clay. The individual blades were cast in silicone, and the best were selected to make it to the second phase. The blades were set at a pitch of two and held together by a center post. They were then cemented to a hobby propeller nose cone modified to hold the propellers. The prototype then had the connection between the nose and blades smoothed out one last time before making a two part mold of the propeller using silicone. The mold box was prepared using a section of our thruster housing pipe conduit and clay. The clay was formed to an ideal second mold half, and the propeller was laid in on top of it. The first half of the mold was poured and allowed to cure for two days. Then the second half of the mold box was prepared by removing the clay and sliding the conduit over the existing mold. Mold release was applied to the surface of the silicone to prevent sticking and allowed to dry. Then the second half was poured and allowed to cure for an additional two days. The casting compound used is called Alumilite, and is mixed in equal proportions to make 2 fluid ounces for each propeller. This is immediately poured and the mold assembled. After 30 minutes, the parts are removed and mold lines cleaned. The propeller is then finished.

The last piece that was manufactured for the motor assembly was the motor housing tube. This tube was made of 5 inch diameter PVC pipe which made manufacturing the housing extremely difficult. The housing needed to be cut in a manner that made the cut plane as close to perfectly perpendicular to the tube as possible. This was accomplished by purchasing a pipe cap that fit over the pipe to hold into a lathe. After the pipe was surfaced it was then put on the CNC machine to drill the holes that will mount the housing to the brackets and motor pressure vessels.

The decision to machine the pieces 'in house' for the ROV was made last semester. This decision was both beneficial and detrimental to our project. The benefit of machining the pieces 'in house' is cost. The cost to CNC aluminum ranges from $500 to $1000 per piece because of the complexity, low volume, and the salary of the individual that does the work. Since the machine shop on campus has the tools, the cost to manufacture all of the aluminum pieces, were absorbed by CSUS. The CSUS staff was able to adhere to the tolerances as well as retain an aesthetic appearance. Of course machining 'in house' has had its drawbacks which mainly consist of time and communication issues. Since there are only 2 machinists and 8 senior project groups, the parts that were submitted did not get complete until the end of April and some of the parts that were made had to be redone because the machine shop staff misread the applicable drawings.

Project Complications

Over winter brake there were many changes to the basic design of the project which caused a major overhaul of our official drawings. Not only were there changes made by the group but there were corrections that needed to be made to our drawings that were recommended by the professor from the previous semester. Once these changes to the drawings were approved, work orders for the parts to be machined were written. Once the work orders were approved, the machinist requested that we make further changes in order to ease fabrication of the parts which caused further delay.

Though we are indebted to the hard work of the machine shop it became our largest holdup. Most of our drawings were given to the machine shop in bulk. This should not have been a problem, but we did not prioritize the parts to a specific order in which they needed to be done. This was a costly mistake because the machinist worked on all the parts at the same time instead of completing one part and beginning the next. This caused all of the parts to be unavailable to us for the majority of the semester. Also, this did not allow us to have parts, such as the motor pressure vessels, which could have been assembled and tested outside of other parts of the ROV. To help speed up the process, group members helped by starting to machine less complicated parts that the machinist could finish later.

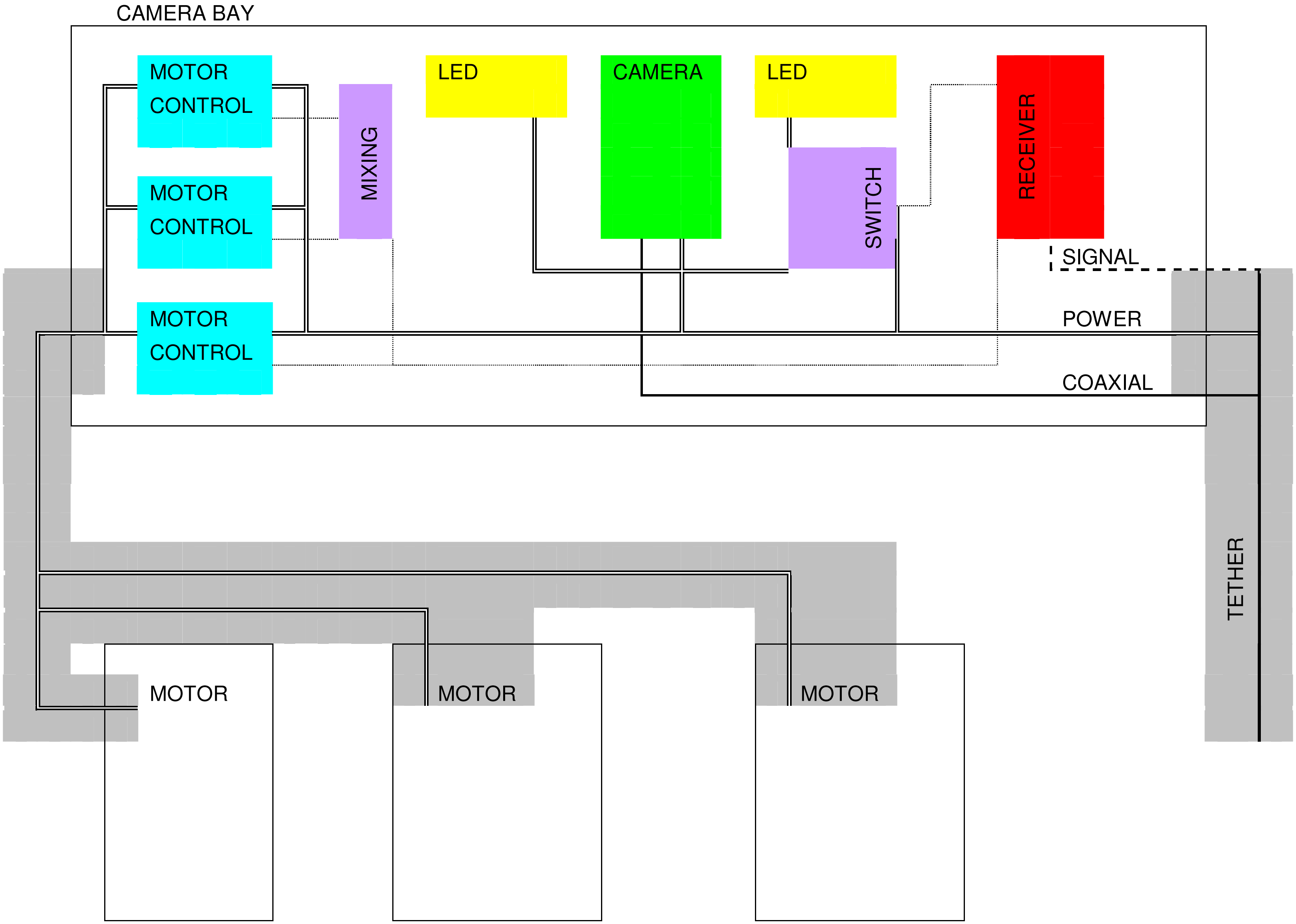
Finally, as the end of the semester was coming and more pressure was on the machinist, our parts were returned at a more reasonable rate but with more errors. These errors were large enough as not to be dismissed and consequently, the parts had to be resubmitted. Some of the mistakes included clearance holes where there should have been tapped holes as well as chamfering both sides of parts when the drawing required only one. We appreciate the work that was done for us, but these errors cost us a great deal of time that could have been used for testing.

Other holdups included time delays with corporate donations and funding. The cable for the umbilical and the buoyant foam were two of these donations. The cable is an important aspect to our project because it sends the power to the ROV. The problem we experienced with the cable company was the promise to receive the cable and then they suddenly decided not to donate the cable. We had assumed that there would be no problems with the cable and had moved our attention on to other parts of the project when we received the company's decision. Luckily, we had chosen to change the depth of the ROV to only 100 ft and were able to find a company that donated this amount of cable and had it to us in two days. We had about the same problem with the donation of the foam.

As college students we had to rely on outside funding from grants to pay for many of our parts. This resulted in a minor holdup in that we had to wait for deadlines that were in the middle of the semester and our requests would not be reviewed until after the deadlines. Even though we had these problems, the project was finished in time and we were able to do some testing. We really appreciate the help that others have given us. When some of our donations fell through, we found companies that would give the same donations and had them to us in a very short period of time. Without this help we probably would not have finished this project on time.

"Flying Eyeball" Cost Analysis

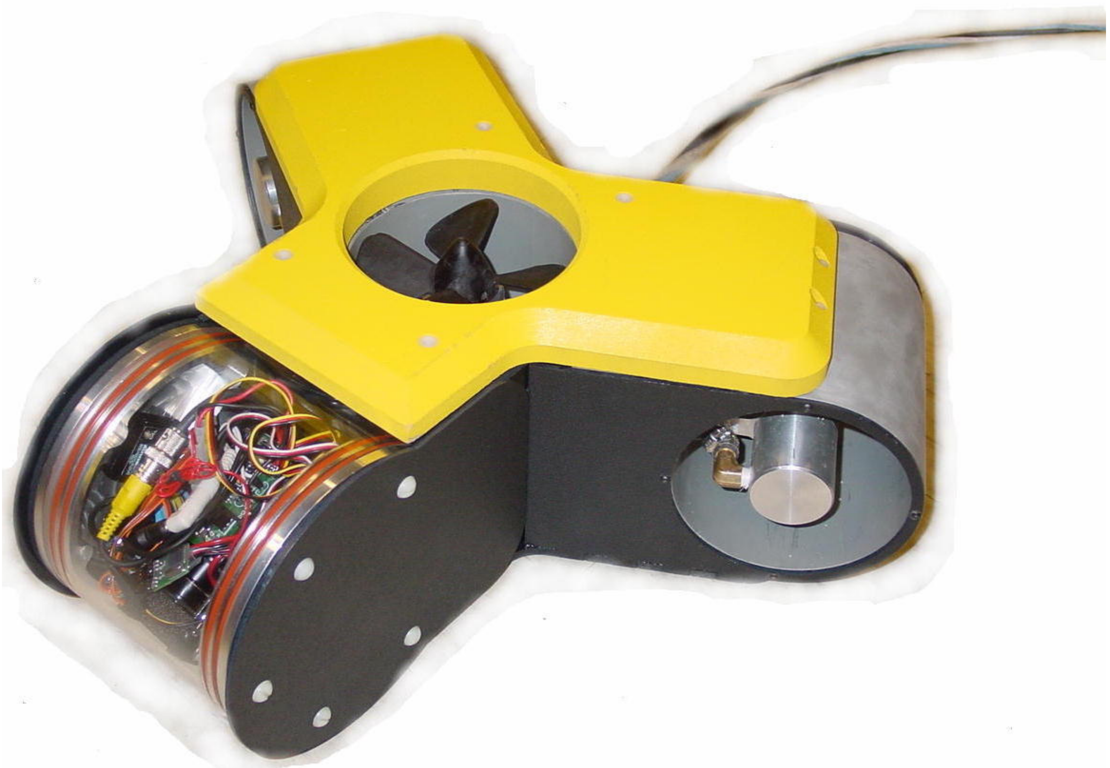
Item Description	Quantity	Price	Total
Umbilical Cable	1	0	**Donated**
Syntectic Material	4	0	**Donated**
Motor Controller	3	31	**$93.00**
Motor	3	21.3	**$63.90**
4mm to 6mm Rigid Coupler	3	7.37	**$22.11**
(4mm) 1/8 Rotary PTFE Seal	3	23.1	**$69.30**
4mm Flanged Bearing	3	2.41	**$7.23**
4mm 3-Blade Nylon Pusher Propeller	3	0	**$0.00**
Camera	1	175	**$175.00**
PVC Conduit Pipe (price is per foot)	10	2.45	**$24.50**
ABS Sheets	1	50.38	**$50.38**
Light Emitting Diode	2	45	**$90.00**
Servo	1	13.99	**$13.99**
Aluminum Stock price bar	4	20	**$80.00**
Aluminum Plate	1	10	**$10.00**
Acrylic Cylinder	1	20	**$20.00**
O-rings	3	2.16	**$6.48**
Aluminum Shaft	1	3.14	**$3.14**
Misc. Tools	1	168.38	**$168.38**
Laser Cutting Fee	1	69.75	**$69.75**
Screws and Bolts	1	99.9	**$223.47**
Total	**47**	**424.16**	**$1,190.63**


CAMERA BAY
MOTOR CONTROL
MOTOR CONTROL
MOTOR CONTROL
MIXING
LED
CAMERA
LED
SWITCH
RECEIVER
SIGNAL
POWER
COAXIAL
TETHER
MOTOR
MOTOR
MOTOR

FMEA NO.	FAILURE MODE AND EFFECTS ANALYSIS	REVISION
	SUMMARY CHART	SHEET 1 OF 1

SYSTEM ROV	PREPARED BY Charlotte Pelker	DATE 11/29/04
SUBSYSTEM Camera Bay	APPROVED BY	DATE
FMEA DATE 11/29/04	REVISED	OPERATIONAL MODE Underwater

PART NAME AND NUMBER	PART FUNCTION	FAILURE MODE	EFFECT(S) OF FAILURE	CRITICALITY 1 - LOW 10 - HIGH S	P	C	CONTROL MEASURES AND SUPORTING ANALYSIS
#-0 Camera Camera	Lever	Loss of lubrication	Camera will not focus	5	1	5	n/a
Camera	Lever	Wear	Camera will not focus	5	1	5	n/a
Camera	Wiring	Damage to wires	No power to camera	5	4	20	Maintain clearance around wire
Heat sinks	Wiring	Overload of electricity	Short/ No output	3	1	3	Make sure components are shielded from each other
Motor Controller	Power Cord/ Wiring	Wear	No power to motor				Reduce cord movement
Motor Controller	Connectors	Short Circuit	No power to motor	6	3	18	Check for wire interference
Motor Controller	Connectors	Fried Ciricuit	No power to motor	4	2	8	Monitor amperes from power supply
Seals	O-rings	Fatigue	Leak	10	4	40	Check seals for integrity before each submersion
Seals	O-rings	Non-conforming	Leak	10		0	Inspect rings before using
Camera bay	Acrylic Case	Pressure fatigue from wear	Leak	10	6	60	n/a
Camera bay	Acrylic Case	Misalignment	Leak	10	9	90	Machine alignment reference points
Camera bay	Acrylic Case	Cracks from foreign objects	Leak	10	10	100	n/a
Camera bay	Aluminum Cap	Lower limit tolerances exceeded	Leak	10	4	40	have machine shop machine instead of project group
Camera bay	Aluminum Cap	Groove not machined well	Leak	10	8	80	have machine shop machine instead of project group
Camera bay	Penetrator	Tolerance on hole is incorrect	Leak	10	7	70	have machine shop machine instead of project group



Recognition:

This project would not have happened without the **financial backing of CSUS**, for which we are very grateful. Thanks also goes to the **faculty and staff of CSUS** for helping in any way they could.