Prototype ROV Final Report

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Executive Summary

Team Library has designed a prototype ROV in response to BP's project request seeking prototypes for rapidly-deployable ROVs to be used for inspections or repair in the Gulf of Mexico. The ROV will eliminate the need for human divers in hazardous offshore areas. Team Library has built and tested a ROV to suit BP's operations.

Specific requirements include having a mass below 15.0 kg, fitting within the size constraints of 58cm x 40cm x 30cm, carrying a payload with a camera, and having a tether attached to the vessel. The thrusters must be securely attached within in the floodable PVC frame and the ROV must be able to travel in all directions with a max speed of at least 0.5 m/s.

Our ROV, *Ugli Dude*, is a rectangular box with dimensions 49.5cm x 21.4cm x 18.5cm (see Figure 1 on page 4). We found the best way to combat drag was to make our design as space-efficient and cost-efficient as possible with a narrow, rectangular frame. The top is lined with aluminum water bottles that can be filled with water to achieve a slight negative buoyancy. The main feature of our ROV is that the thruster placement is modular by use of "utility ports", which allow us to move the thrusters to different locations on the ROV. Our ROV had an overall cost of $124.95, which was below the average cost among all ROVs.

There are two different configurations for our ROV: the *Ugli* which prioritizes maneuverability, and the *Dude* which prioritizes speed. The *Ugli* (maneuverable) configuration has two thrusters that extend off the side of the ROV to allow it to turn quickly, and another thruster facing upwards to control vertical movement. It also has a mechanical arm to make underwater manipulations easier. This can be removed for other configurations to lower overall weight and drag of the ROV. The *Dude* (speed) configuration has all the thrusters unshrouded and facing backwards inside the ROV, making it significantly faster than the other configuration. The *Dude* can be seen in Figure 1(a) and the *Ugli* can be seen in Figure 1(b) on page 4.

We tested the ROV in the GFL preliminary testing tank, the Marine Hydrodynamics Laboratory (MHL), and Canham Natatorium. Through the speed tests at the MHL, we found that the *Dude* has a maximum speed of 0.743 m/s, making the *Ugli Dude* the second fastest ROV in the competition. In the maneuverability tests at the Natatorium, we were able to complete the maneuverability competition in 2 minutes and 49 seconds with the *Ugli* configuration. This was the fastest time in the competition; however, the data collected lacked sufficient detail and our runs were disqualified.

For the full scale version of our prototype ROV, we recommend that the PVC frame be replaced with TIG welded aluminum. Aluminum is stronger and anti-corrosive which will allow it to better handle the warm and shallow salt water environment. Aluminum will also transfer heat from the lithium ion battery and related electronic components to the surrounding water, preventing the electronics from overheating. Structural improvements to the full-scale ROV include adding an upward facing thruster to the bottom of the ROV, a hydrodynamic shell surrounding the ROV, and a complex mechanical arm to assist in intricate underwater tasks. This report details our design of our prototype ROV, performance results, and full-scale analysis.

Introduction

BP has requested proposals for prototype rapidly-deployable ROVs for inspections or repair in shallow, offshore area in the Gulf of Mexico. Team Library was tasked with building and testing a prototype ROV that may be scaled up to suit this environment. The full-scale version of the prototype ROV must be designed to withstand turbulence and temperature changes in the Gulf of Mexico. We are confident that our full-scale ROV would perform well for BP's operations.

Team Library's design meets BP's requirements and addresses environmental constraints in both the prototype and our full-scale design. Our prototype ROV, the *Ugli Dude*, has a floodable, cemented frame designed to fit the canister and has a video camera that allows the human operator to guide the vehicle. The ROV must have all six degrees of freedom in order to perform the tasks in the maneuverability competition, which include turning a valve and hovering to read a data board.

The Ugli Dude has two configurations: the *Ugli* which prioritizes maneuverability, and the Dude which prioritizes speed. In order to easily adjust the ROV's depth and hover, we placed one upward-facing thruster at the center-top of the *Ugli* configuration. To minimize our turning radius in the *Ugli* configuration, we designed removable wings with thrusters on the ends to attach to each side of the ROV. The wings increased the lever arm of the thruster force, thereby increasing the torque on the ROV due to the wing thrusters (Li et. al., 2014).

In the *Dude* (speed) configuration we placed the four thrusters horizontally facing out the rear in order to align the thruster power with the drag of the ROV and thereby maximize speed (Li et. al., 2014). Reference Figure 2(a) on page 4. Team Library's design was influenced by research indicating that good water flow through the frame results in a lower drag coefficient for an underwater vehicle (Sayer, 1993). We also minimized drag by making the frame space-efficient.

We predict that our design will be very stable which will allow it to maneuver in turbulent conditions. We plan to use a large lithium ion battery which would shift the center of gravity downward and make the full scale ROV slightly more stable (see Figures 8(a) and 8(b) on page 12). The ROV will be mainly built with aluminum, which is strong, anti-corrosive, and transfers heat quickly. This feature will protect the electronics from overheating in higher water temperatures (Rafanelli, Robinson, 2000).

Design Overview

The ROV was designed to be competitive in both speed and maneuverability. The *Ugli Dude*'s modular design allows for two different configurations that favor either power and hydrodynamics or stability and versatility, permitting optimal performance in both speed and maneuverability-intensive situations. The Dude was designed to travel above 0.5 m/s in the speed competition. The Ugli was designed to perform the tasks in the maneuverability competition, which include turning a valve and hovering to read a data board. See Figure 1(a) and 1(b) on page 4 for depictions of the ROV in the speed Dude and maneuverability *Ugli* configurations with major components labeled. Additional pictures of both configurations can be seen in Appendix 1-10.

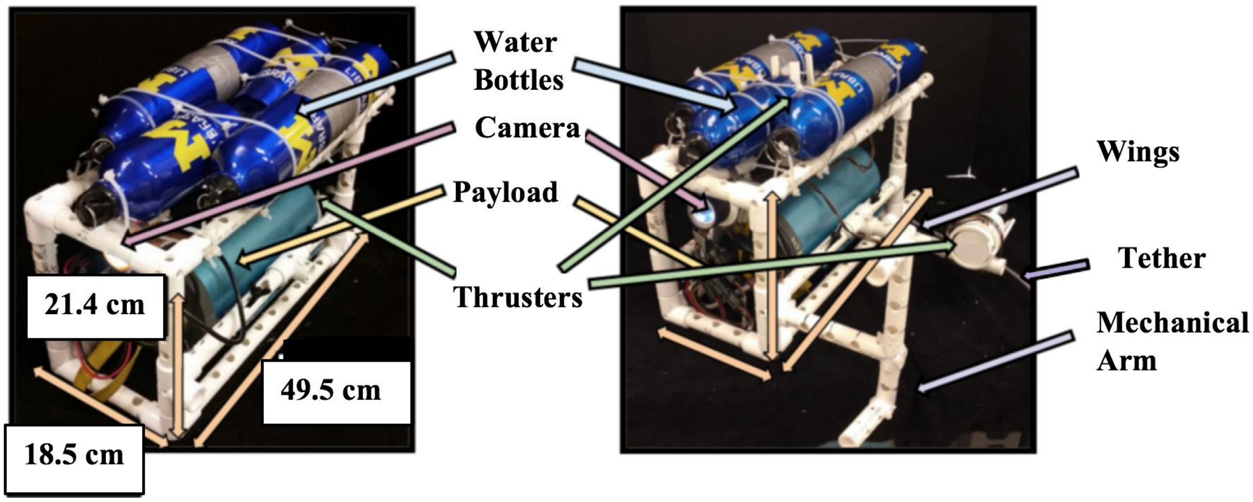

Figure 1. (a) *Dude* configuration (left) and (b) *Ugli* configuration (right).

Frame Design. A rectangular PVC frame encases the canister, camera, and shroud-less thrusters, preventing each from damage. The reason we chose this design was because it minimizes cost by using less PVC and fewer PVC joints, and it reduces construction time due to its simplicity. The width of the ROV was chosen to just allow the canister to fit in from the bottom and to secure it without extra rails. We minimized drag by making the frame space-efficient while ensuring that there was good water flow through the open frame. We drilled many upward-facing holes in the frame to prevent the formation of air bubbles, which may disturb the vehicle's buoyancy.

Thruster Placement. Two distinct thruster configurations allows the ROV to adapt to the needs of different tasks. The thruster placements can be seen in Figure 2(a) and 2(b).

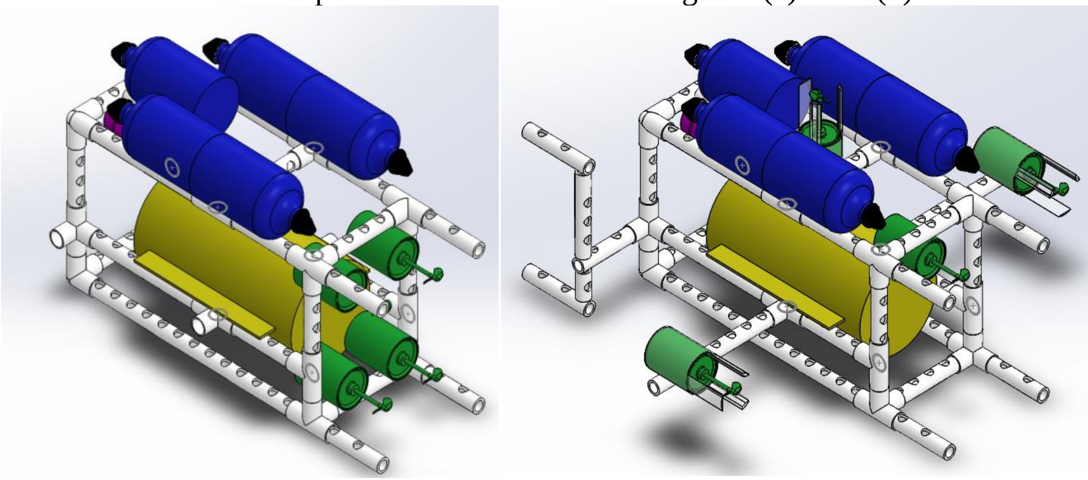

Figure 2. (a) *Dude* configuration (left) and (b) *Ugli* configuration (right) with thrusters (green), canister (yellow), water bottle floatation (blue), camera (pink) and PVC Frame (white)

Dude Configuration. Our research into hydrodynamics influenced our thruster placement. ROV thruster systems are often designed so that hydraulic drag and thrust are positioned on the same line to have better stability and control (Li et. al., 2014). For this reason, all four thrusters will face backwards horizontally in the *Dude* configuration. To maximize speed, it is best to have all thrusters close together.

Ugli Configuration. To maximize maneuverability, it is best to create distance between the vectored thrust and the vehicle's center of mass, thereby increasing the torque on the vehicle (Li et. al., 2014). For this reason, two of the thrusters were on PVC wings for the *Ugli* to increase the thrusters distance from the center of mass.

For maneuverability, we also saw it necessary to be able to hover and travel vertically. To do this we added a vertical thruster above the center of mass. To decide which orientation this thruster would point, we considered that as the ROV became closer to the pool bottom, more of its tether would be supported by the pool floor. For this reason, we thought the ROV would become slightly more buoyant as it traveled downwards due to a slight loss of mass. We placed a thruster pointing up to provide maximum downward thrust to counteract any gains in buoyancy.

The sum of the drag coefficients in all of the x, y, and z directions has a minimum when the yaw angle is approximately 0 degrees (Avila et. al., 2011). To ensure that the yaw angle of the vessel during its journey is approximately 0 degrees, a thruster will be placed on the top rear of the vessel with twice the distance to the centerline than the two thrusters below centerline to balance the moments. Refer to Figure 2(b) on page 4.

PVC Wings. Removable wings are mounted on both sides of the ROV provide attachment for thrusters during the maneuverability test. They can be seen in the *Ugli* configuration in Figure 1(b) on page 4. They are mounted in the "utility ports", which are PVC tee connectors that branch off the side of the frame and can be seen in Appendix 11. Shrouds permanently mounted to each arm allow for easy removal or installation of the thrusters when transitioning between speed and maneuverability operations as well as allow for protection of the thrusters. These wings can be removed when the *Dude* configuration is desired.

Flotation. We used five water bottles for floatation and their placement can be seen in Figures 2(a) and 2(b) on page 4. The four water bottles along the sides are sealed and empty, while the water content of the front water bottle is adjusted such that the ROV achieves a slight negative buoyancy. The water bottles are placed at the top of the ROV with the intent to raise the center of buoyancy, increasing the vessel's stability.

Camera Placement. The camera is placed at the front of the ROV within the PVC frame, ensuring an unobstructed view of the data board as well as protection from damage. Since it was pointing out of the center of the ROV it allowed for ease of driver control when hitting the paddle. The camera's placement can be seen in Figure 1(b) on page 4.

Control System. The control box consists of four switches that allow each thruster to be operated individually in forward or reverse. Our control system has an additional button that powers all forward thrusters. This feature is designed specifically with the speed configuration in mind. The operator was able to activate all thrusters simultaneously so no thruster would start earlier than the others, which could cause an initial bias in the trajectory of the vessel.

We also found that if a thruster was put both into forward and reverse on the controller, the thruster would actually receive no power. We found this to be beneficial, because even while the button is in use, forcing all the thrusters forward, the toggles can still be used to temporarily cut power to individual thrusters. This allows the operator to slightly adjust trajectory while still maximizing forward thrust. A picture of the control box can be seen in below in Figure 3 on page 6and the wiring schematic can be found in Appendix 12.

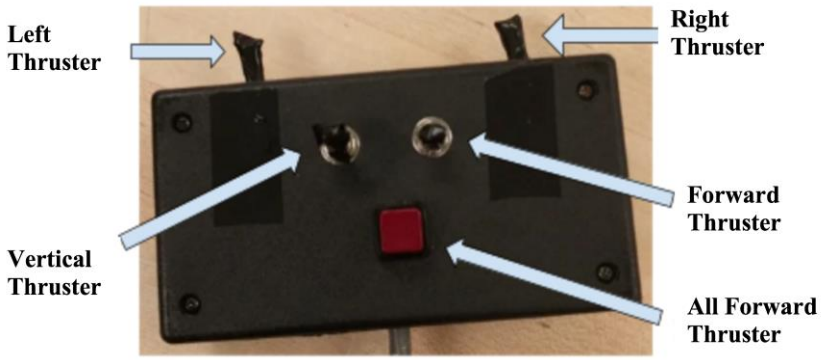

Figure 3. Control box used to operate the ROV

Model Description

Simplified Mass Budget. The detailed mass budget is located in Appendix 13. Table 1 displays a simplified mass budget for the ROV.

Table 1. Simplified mass budget of the ROV.

Parts	Mass (g) *Dude*	Mass (g) *Ugli*
PVC Structure	1605.7	2080.3
Thrusters	905.6	905.6
Payload	7511.8	7511.8
Buoyancy	374.5	374.5
Ballast	434.9	70.3
Miscellaneous	17.8	20.5
Total	**10950.3**	**10963.0**

Cost Estimate. The preliminary ROV design costs approximately $124.95. Reference Appendix 14 for the amount and cost of each type of component.

Center of Mass. To determine the ROV's center of mass, we used the equation:

$$CM = \frac{\sum m_i r_i}{\sum m_i} \quad (1)$$

where *CM* is the position of the center of mass with respect to a preset origin depicted where the three arrows meet in Figure 4, m_i is the mass of a ROV component, and r_i is the distance from the origin to the center of mass of that component.

We were able to accurately determine the center of mass by using Solidworks. After constructing the CAD models of the ROV, we input the material properties of every component of the ROV and used a program in the Solidworks library that utilized the masses of every component and their location with Equation 1 to determine the center of mass for both configurations. This point is shown with dimensions in Figures 4(a) and Figure 4(b) on page 7.

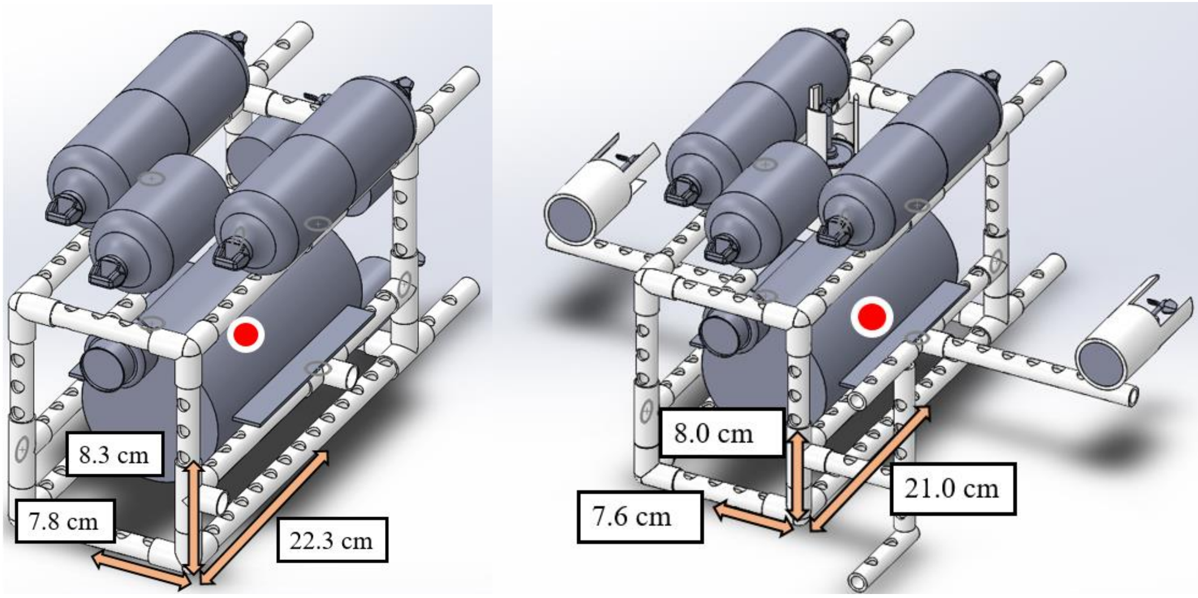

Figure 4. Center of Mass for the (a) *Dude* configuration (left) and (b) *Ugli* configuration (right)

Center of Buoyancy. To determine the ROV's center of buoyancy, we used the equation:

$$CB = \frac{\sum V_i r_i}{\sum V_i} \tag{2}$$

where *CB* is the center of buoyancy, V_i is volume of an ROV component, and r_i is the distance to from the origin to the center of volume of that component.

We were able to accurately determine the center of buoyancy using Solidworks. Similar to the calculation for the center of mass, we used our CAD models of the ROV, set every solid part of the ROV to have the density of water and then applied the program to calculate the center of mass on the ROV's water weight. Since all of the volume had the same density, this calculation's answer becomes identical to answer derived using Equation 2. The center of buoyancy with dimensions is shown for each configuration in Figures 5(a) and 5(b).

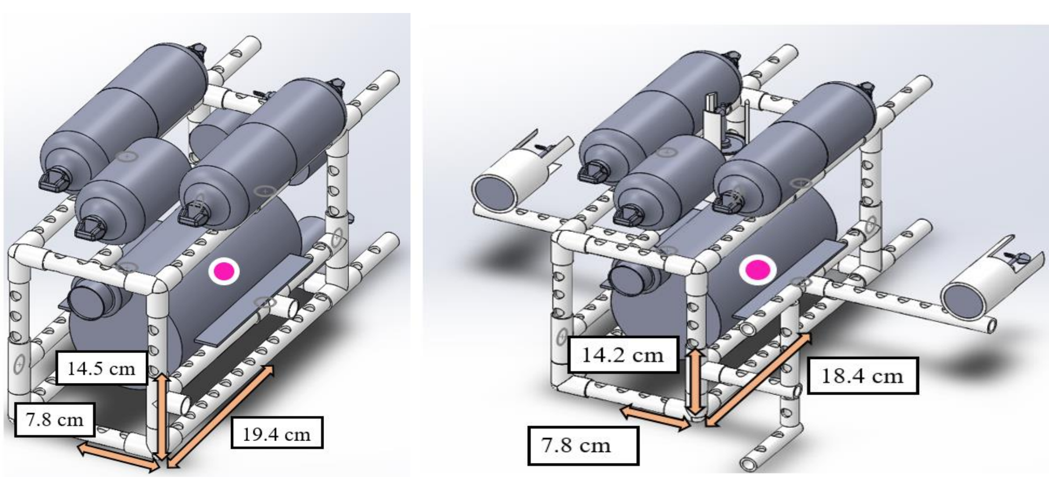

Figure 5. Center of Buoyancy for (a) *Dude* configuration (left) and (b) *Ugli* configuration (right)

Stability Analysis. There are two design elements that cause the ROV to have a slight upward pitch. First, the center of buoyancy is not directly above the center of gravity for both configurations (see Figure 6(a) and 6(b)). Instead, it is front of it. The moment that is caused by the slight misalignment can be seen in Figures 6(a) and 6(b). Second, the vessel has two thrusters below center of gravity in the *Ugli* configuration, which also contributes to the upward pitch. This pitch aids the ROV to travel upwards.

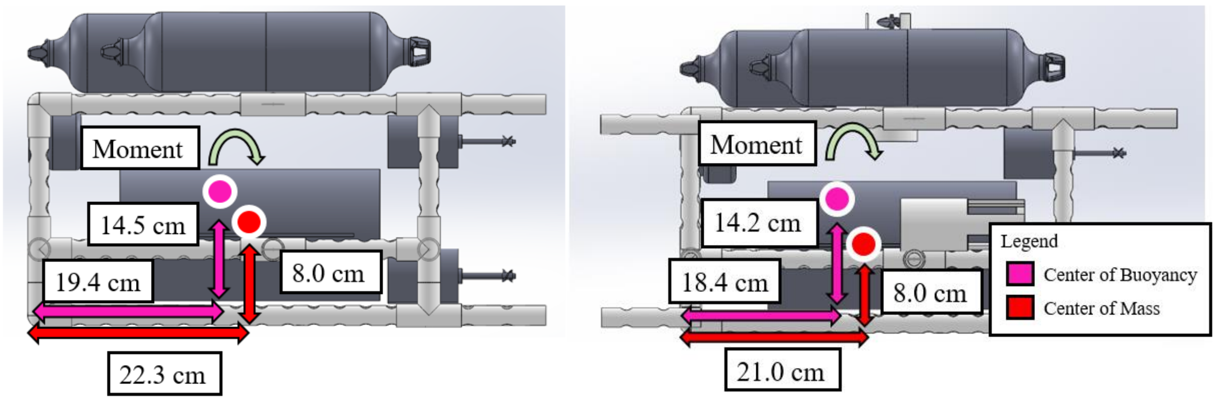

Figure 6. The top pink dot represents the center of buoyancy while the bottom red dot depicts the center of gravity of (a) the *Dude* configuration and (b) the *Ugli* configuration

Thruster Testing. To decide where to place each thruster, we tested the thrust output of each thruster. Our testing data can be found in Appendix 15. We found that there were some variances between our four thrusters; however, thrusters three and four are the most similar, noted by the asterisk. This makes them good candidates to be used for on our PVC wings. From our testing data, we calculated the power of the prototype vessel to be 11.19 W.

Shroud Testing. We decided to create a minimalist shroud out of 2in diameter PVC. We cut it to have three 0.5" wide slit that are 100 degrees apart to try and minimize how it affects thrust output. From our testing we found that there is a 3.8% thrust decrease in the forward direction and a 0.8% thrust decrease in the reverse direction by using these shrouds on our thrusters. We saw this as negligible due to possible error in our thruster testing set up. Our data from testing can be found in Appendix 16.

Model Performance

This section describes how the *Ugli Dude* performed in tests, including associated calculations. The *Ugli Dude* was assessed in three rounds of testing: preliminary GFL testing, official MHL speed testing, and Natatorium competition maneuverability testing.

Anticipated Top Speed. To determine the anticipated top speed of the ROV, *V*, we used:

$$D = C_D \frac{1}{2} \rho A_{ROV} V^2 \quad (3)$$

where *D* is drag, approximated with thrust: 23.1 N; $C_D$is approximated by the coefficient of drag of a square: 1.05; $\rho$is the density of fresh water at 20°C: 1000 kg/m^3; and $A_{ROV}$is the cross-sectional area of the front of the ROV: 0.0589 m^2. From this equation, the top speed is anticipated to be 0.864 m/s.

Preliminary GFL Testing. On March 28th, our team was able to test our ROV's *Dude* configuration in the tank at GFL. See Appendix 17 for a corresponding testing image. During this testing, we discovered the slight upward pitch talked about in the Stability Analysis section. We also found that the ROV veered left rather than moving in a straight line. We believe the thrust output of each of the four thrusters was more varied than we had anticipated from our thruster testing. We found that in order to travel straight the operator had to cut one of the more powerful thrusters every few seconds.

We were satisfied with the results of our GFL speed testing; our top speed was approximately 0.6 m/s, which surpasses the 0.5 m/s standard, and we estimated our turning radius at 0.5 m as the ROV turned 360 degrees using the full width of the tank.

Official MHL Speed Test. Speed testing in the Marine Hydrodynamics laboratory required the ROV to travel 30 ft in under 18.3 seconds for a minimum speed of 0.5 m/s from a running start. See Appendix 18 for a testing image. Three such successes were required, and of these three, our fastest, indicated in Table 2, was 0.743 m/s, lower than our predicted speed. Despite placing second, the *Dude* veered right during the testing, prompting thruster and buoyancy adjustment to realign the ROV.

Table 2. Official MHL Speed Testing Results

Trial	Time (s)	Speed (m/s)
1	12.68	0.721
2*	**12.30**	**0.743**
3	12.86	0.711
Average	**12.61**	**0.725**

Also during this testing, we found that the aluminum water bottles took on some water so we tried to seal the empty ones with PVC cement. This was not entirely effective as the water bottles continued to take on water during the speed test and maneuverability test. In future designs we would recommend the use of a high-strength epoxy.

Actual Coefficient of Drag. After determining the official velocity, V, the actual coefficient of drag of the ROV, C_D, can be calculated through the drag equation:

$$C_D = \frac{T}{\frac{1}{2}\rho A_{ROV} V^2} \qquad (4)$$

where T, the total thrust of the four thrusters, is substituted for drag: 23.1 N;$\rho$is the density of fresh water at 20°C: 1000 kg/m^3; and $A_{ROV}$is the cross-sectional area of the front of the ROV: 0.0589 m^2. From this equation, the actual coefficient of drag of the ROV is 1.421. This value is slightly greater than the approximated value of 1.05, which may be due to water turbulence through the center of the ROV as it travels.

Hydrodynamic Efficiency. To determine the hydrodynamic efficiency of the ROV, η, the following equation can be used:

$$\eta = \frac{P_E}{P_B} \quad (5)$$

where P_E is the effective power of the ROV: 17.2 W; and P_B is the braking power approximated as 125 W from the MHL testing data referenced in Appendix 19. Note that P_E is calculated as $R_T V$, total resistance multiplied by velocity, or TV, thrust multiplied by velocity. From these formulas, η is calculated to be 0.137. Thus the ROV is very inefficient as it only effectively outputs 13.7% of its available power.

Official Maneuverability Competition. The final ROV testing procedure consisted of a competition depicted in Figure 7. The Ugli was tasked to travel to the middle of the pool, turn a paddle 180 degrees, continue to the end of the pool and read three data points from a submerged data board, turn the paddle again, and return to the start. The Ugli completed this task with the fastest time of 2 minutes and 49 seconds but was disqualified because the recorded required data was not to BP standards. However, due to error of the scientists, the data was not detailed enough as there was no visual description of the sea creature. All runs were disqualified. See Appendix 20 for full results.

Besides this error of the engineers, the *Ugli* also became increasingly negatively buoyant as its water bottles took in water throughout the trials. For this reason, we had difficulty hovering to read the data board during the maneuverability competition. In addition, the downward-facing thruster did not provide enough thrust in reverse to propel the ROV up quickly. However, besides the vertical movement, the *Ugli* had excellent handing and no maneuverability or controls issues. The ROV turned the paddle smoothly due to the mechanical arm and there were no issues with the ROV rising to the surface or getting stuck on the bottom.

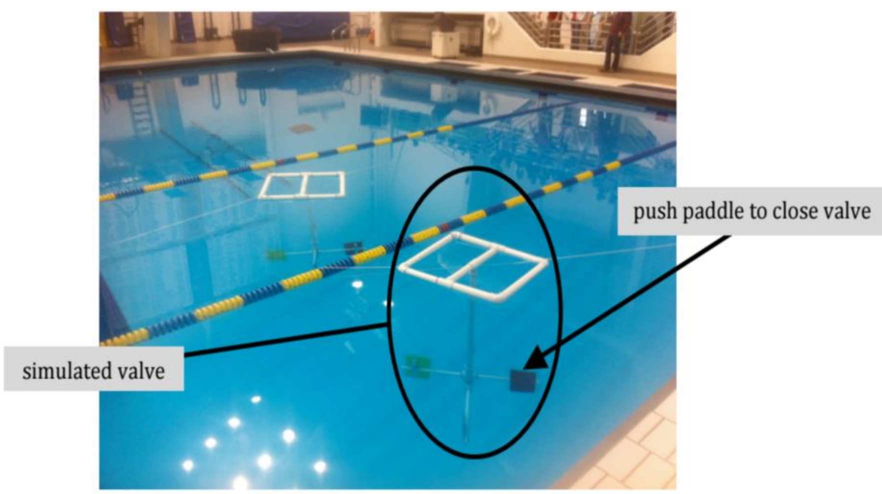

Figure 7. From Coursepack: view of Natatorium maneuverability competition procedure.

Full-Scale Performance

We used BP's recommended scale factor of 2.5 to geometrically scale our prototype to a full-size ROV. The full-size dimensions will be 1.24m x 0.535m x 0.463m.

Scaled Mass. Using a cubic scaling relationship, the mass, m_s, of the scaled ROV is calculated through the equation:

$$m_s = \frac{\rho_s}{\rho_m} \lambda_L^3 m_m \tag{5}$$

where $\lambda_L$is the linear scaling factor of 2.5, ρ_s is the density of salt water at 10°C: 1027 kg/m^3, ρ_m is the density of fresh water at 20°C: 998 kg/m^3, and $m_m$is the model's mass of 10.95 kg. From these values, the full-scale mass is calculated to be 176 kg. However, this is an underestimate because the new materials for full scale implementation will increase the mass of the ROV. We may need to add buoyancy, which is one reason we plan to use adjustable ballast.

$$V_s = \frac{\lambda_v}{\lambda_L} V_m \tag{6}$$

where $\lambda_v$is the linear ratio of the kinematic viscosity of salt water at 10°C: $1.440 \times 10^{-6}\ m^2/s$, to the kinematic viscosity of fresh water at 20°C: $1.004 \times 10^{-6}\ m^2/s$; $\lambda_L$is the geometric scaling factor of 2.5; and V_m model velocity: 0.743 m/s. From these values, the full-scale velocity is calculated to be 0.426 m/s.

Power Scaling. To determine the minimum power needed to support a full scale ROV, first scale thrust using the drag equation and the new scaled velocity. Then use this scaled thrust to determine the new effective power, which uses Equation 5 to determine the new braking power needing to drive the ROV: 204.82 W. Full calculations can be seen in Appendix 21.

Environmental Scaling. Team Library considered environmental factors such as extreme temperatures and turbulence when scaling up our ROV. In order to minimize fatigue on the tether due to turbulence we plan to use of neutrally buoyant tether. The tether is a Kevlar cable covered with spherical floats that prevent it from sinking. This will also provide unencumbered movement and prevent tether entanglement (Patent CA1142801).

The full-size version will feature a T6 T6061 aluminum frame, as well as adjustable ballast. Aluminum T6 T6061 is used because it is strong, light, weldable, and resistant to corrosion. It is the most widely used material in ROVs today (Beasley, 2000). The full-size ROV needs to be able to travel to deeper depths if needed, where the pressure is higher and temperature is lower. Aluminum is much stronger than PVC and is capable of handling a much higher pressure. Additionally, the adjustable ballast will allow the ROV to compensate for slight differences in buoyancy due to water temperature or depth. We considered active ballast but we believe this is unnecessary for a shallow-water ROV. The adjustable ballast will be achieved by placing compressed air tanks at the center of the vehicle, which may alter the shape of the vehicle as our model has the buoyancy spread out at the top.

Full Scale Stability Analysis. From our material changes we anticipate the CG to move downward from its scaled location on the model, but the CB will remain constant, as seen in Figures 8(a) and 8(b). The CG will shift downwards because of the use of a large battery, which is one of the densest components on the ROV and is near the bottom of our frame. From this we believe the CG will shift downwards closer to the battery. When the frame becomes aluminum, it becomes lighter relative to the rest of the components. Thus from this we believe it will not affect the CG or CB significantly. Since the volume of the components all increase the same relative to each other and since we plan on placing our active ballast over the CB point, we anticipate the CB to not change significantly.

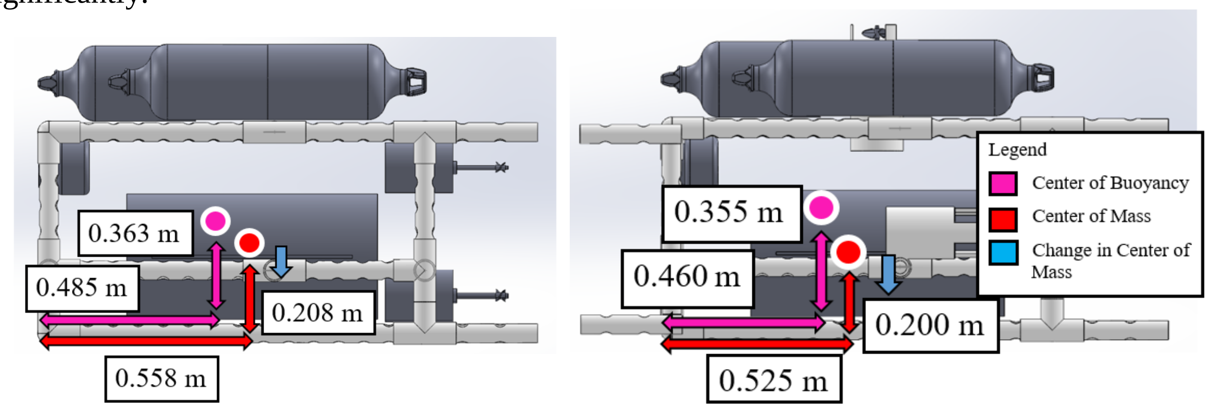

Figure 8. Center of buoyancy and mass of the scaled up ROV for (a) the *Dude* and (b) the *Ugli*.

Recommended Design Changes. In addition to material changes to adapt to the Gulf of Mexico environment, design improvements will be implemented in the full scale ROV. The main challenges of our model design were difficulty with vertical movement and veering due to unbalanced thrust output. We recommend further thruster testing to balance this thrust output. We also recommend placing an upward-facing thruster on the bottom of the frame of the ROV to assist in vertical movement. In addition, the full-scale ROV will not have leaking water bottles on the top of the ROV, which made the model's downward-facing thruster less effective. These changes will improve the vertical movement and hovering capabilities of the ROV.

The *Ugli Dude* excelled in both speed and maneuverability. However, due to error of the scientists, the data was not up to BP's standards and all runs were disqualified. In the future, the scientists will all be well-versed on the objective of the project and focused on collecting high-quality data.

Overall, the *Ugli Dude* performed very well. We would keep the modular design and the full-scale ROV would have utility ports and removable wings for the side thrusters. We would keep the control box because the button plus four toggle switch system was very intuitive and effective for steering. To maximize efficiency, we would remove unnecessary pieces of PVC to reduce cost and drag. These changes are highlighted in Appendix 22.

Team Library has considered design changes that may optimize the performance of the full-scale ROV. We understand the importance of making our ROV hydrodynamic, which is why we would add a hydrodynamic shell over the frame to the full-scale design. In addition, we would design a complex mechanical arm for underwater manipulations because the ROV must perform a variety of technical tasks. We recommend a robotic arm that utilized a hydraulic actuation mechanism to allow it to accurately carry out underwater tasks (Dunnigan, 1996). More testing is required to determine the necessary capabilities of the mechanical arm.

Conclusions

The objective of this project is to create a prototype ROV that will operate well in shallow water. We have met this objective by designing a modular ROV with two configurations: the *Dude* optimizes speed while the *Ugli* optimizes maneuverability. The ROV is designed to perform the tasks in the maneuverability competition, which include turning a valve and hovering to read a data board. We designed a scaled version of our prototype ROV to perform a variety of tasks in the Gulf of Mexico.

We accomplished this with utility ports for the two removable PVC wings for the side thrusters and for the mechanical arm at the front of the ROV. We have locations to put all 4 thrusters at the back when pure speed is necessary. The *Ugli Dude* excelled in both speed and maneuverability. We placed 2nd in the speed competition with a maximum speed of 0.74 m/s. In the maneuverability competition our ROV had the fastest run by far with a time of 2:49 minutes. We achieved this with a fast ROV, with wings to decrease the turning radius, a mechanical arm which latched onto the paddle, and an intuitive control system. However, due to error of the scientists, the data was not up to BP's standards and all runs were disqualified.

Our vessel should perform similarly when scaled up to full-size. The full-scale ROV will feature an aluminum frame, adjustable ballast, neutrally buoyant tether, LED light, lithium-ion battery, and an aluminum shroud to protect the electronics. The ROV will also feature a hydrodynamic shell, an upward-facing thruster for vertical movement, and a robotic arm for underwater manipulations. These design and materials changes will make our ROV, stable, durable, and effective in handling.

If you have any questions concerning this report, or our prototype ROV, *Ugli Dude*, feel free to email us at teamlibrary@umich.edu.

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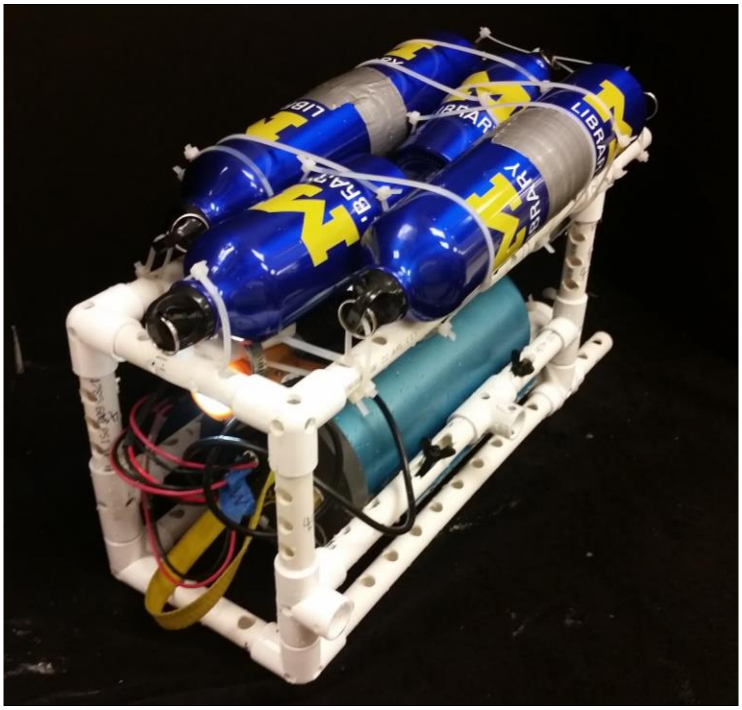
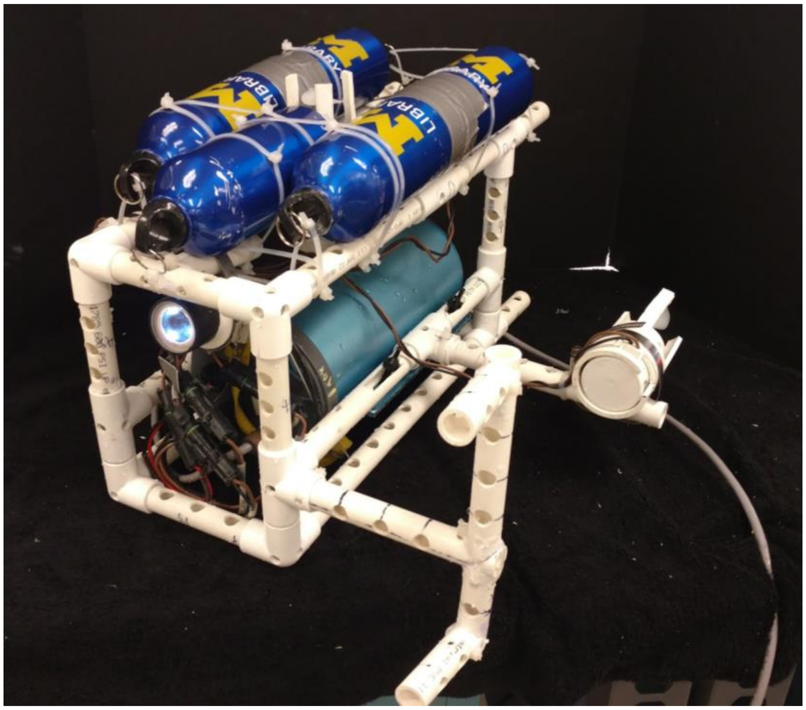
Appendix

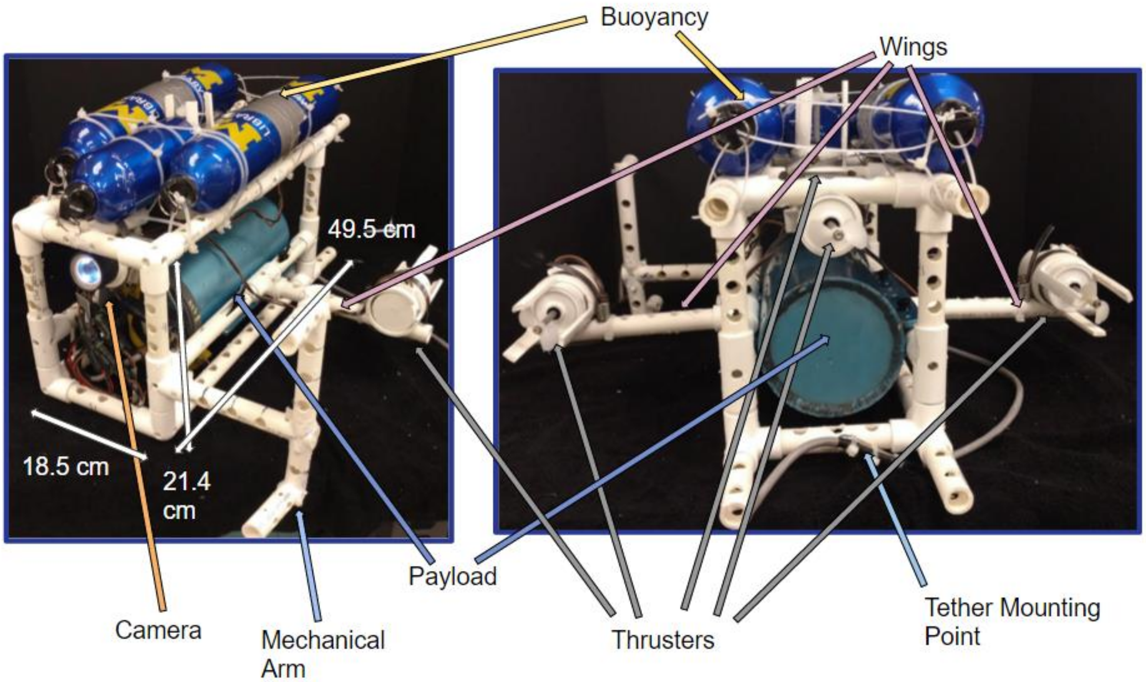
Appendix 1. *Dude* configuration, perspective view.



Appendix 2. *Ugli* configuration, perspective view.

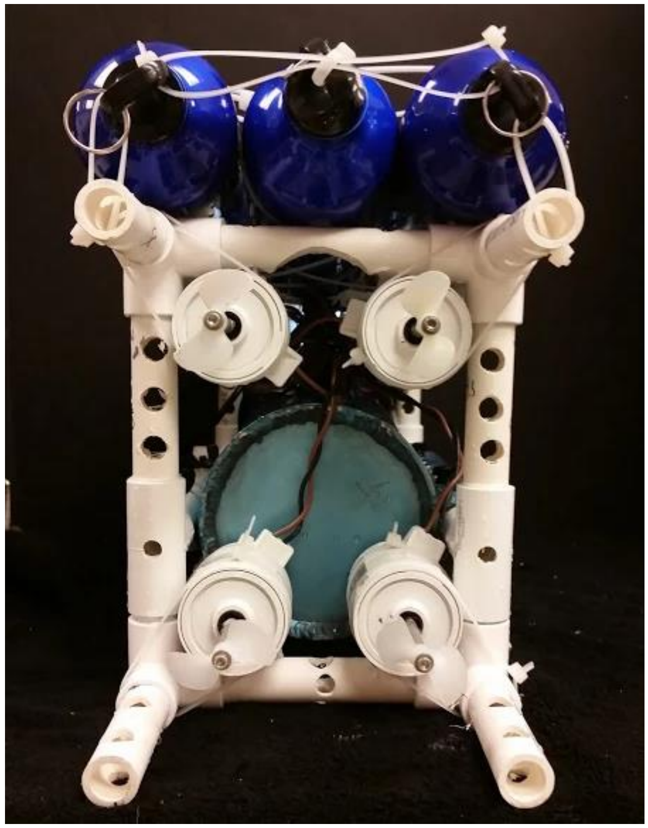


Appendix 3. *Dude* and *Ugli* with major components labeled.

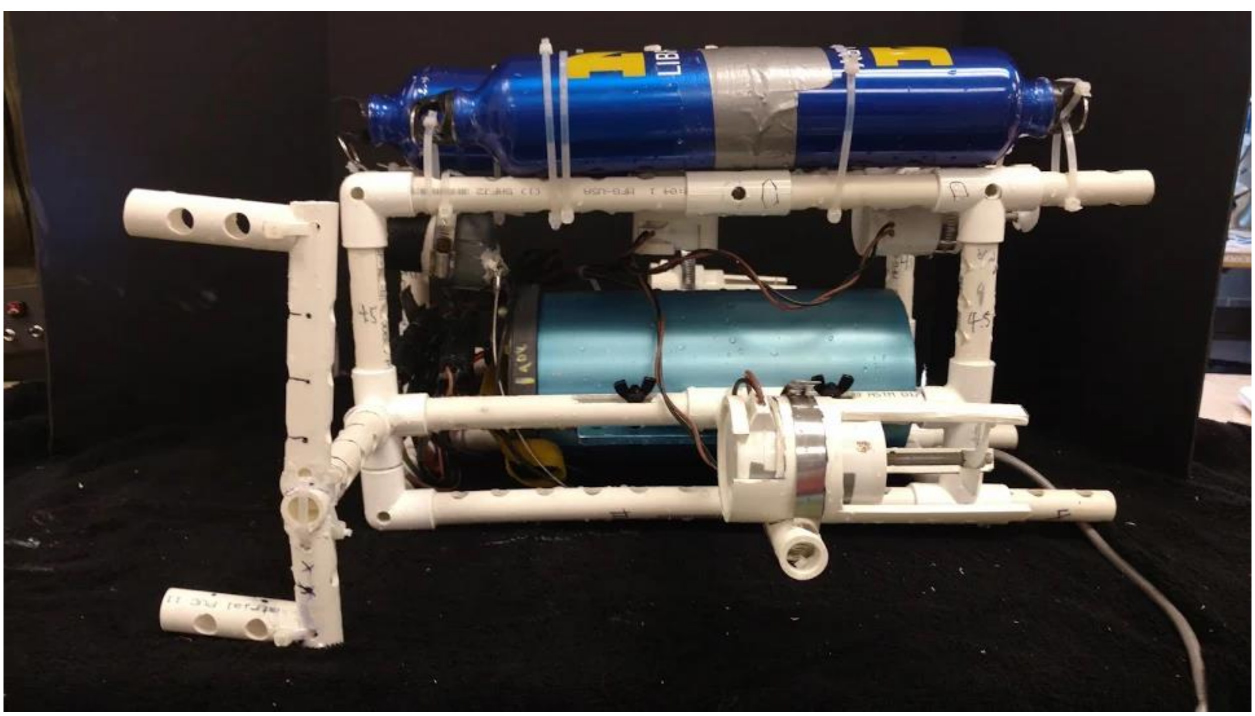


Appendix 5. *Dude* side view.

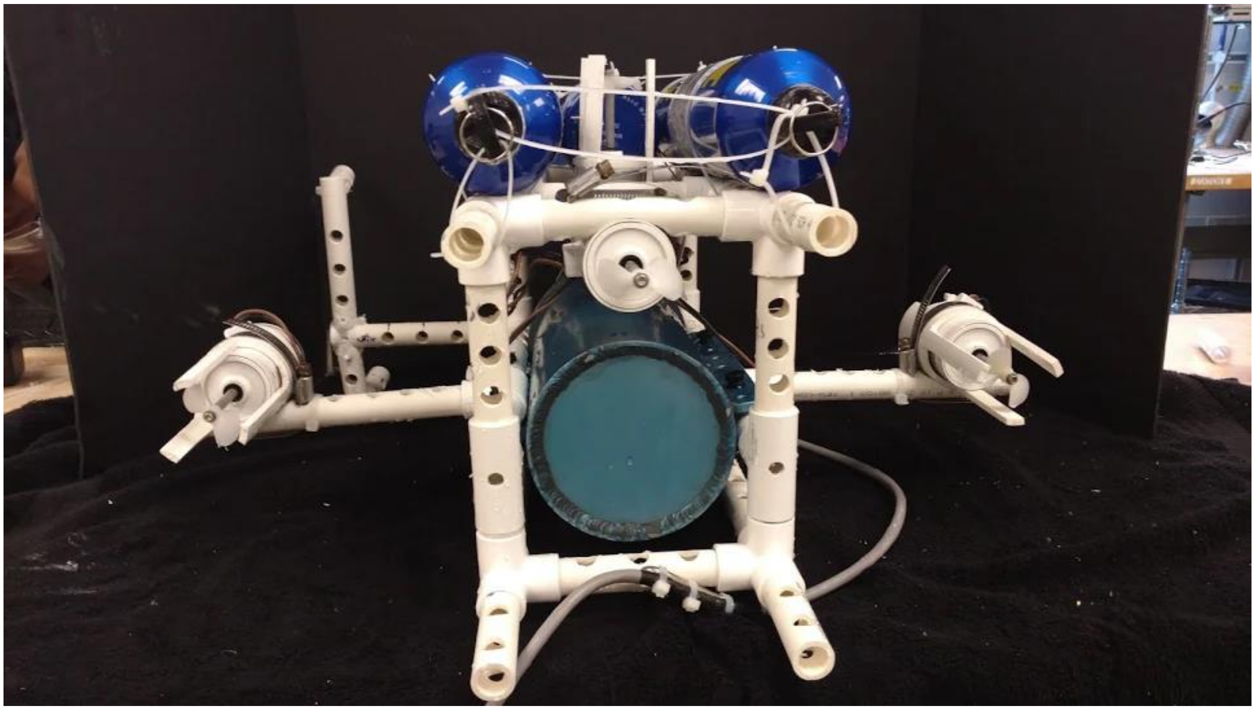
Appendix 6. *Dude* rear view.



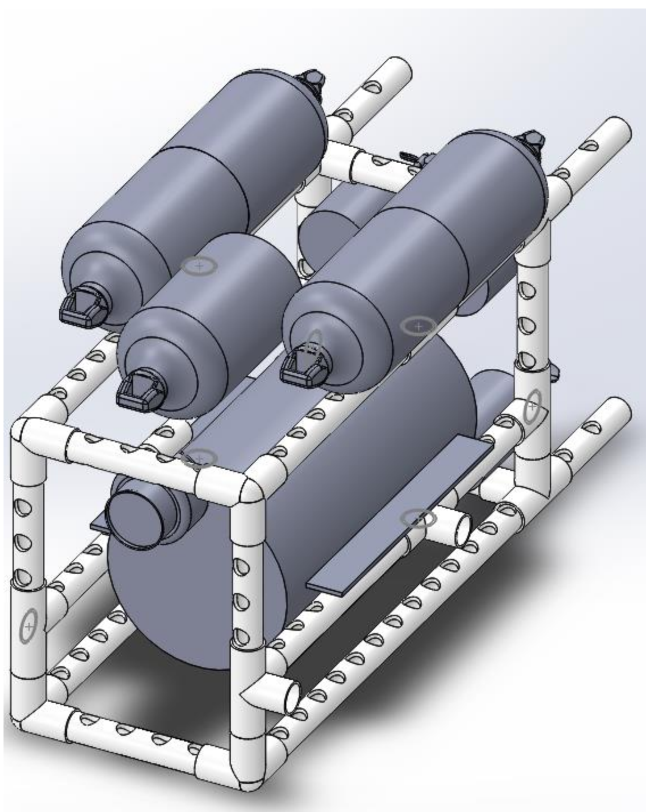
Appendix 7. *Ugli* side view.



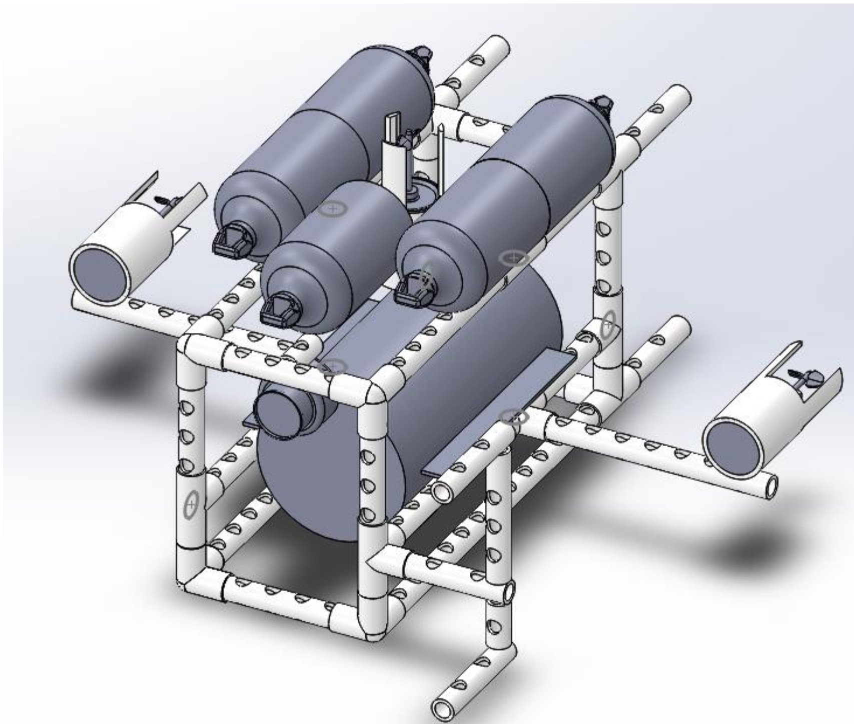
Appendix 8. *Ugli* rear view.



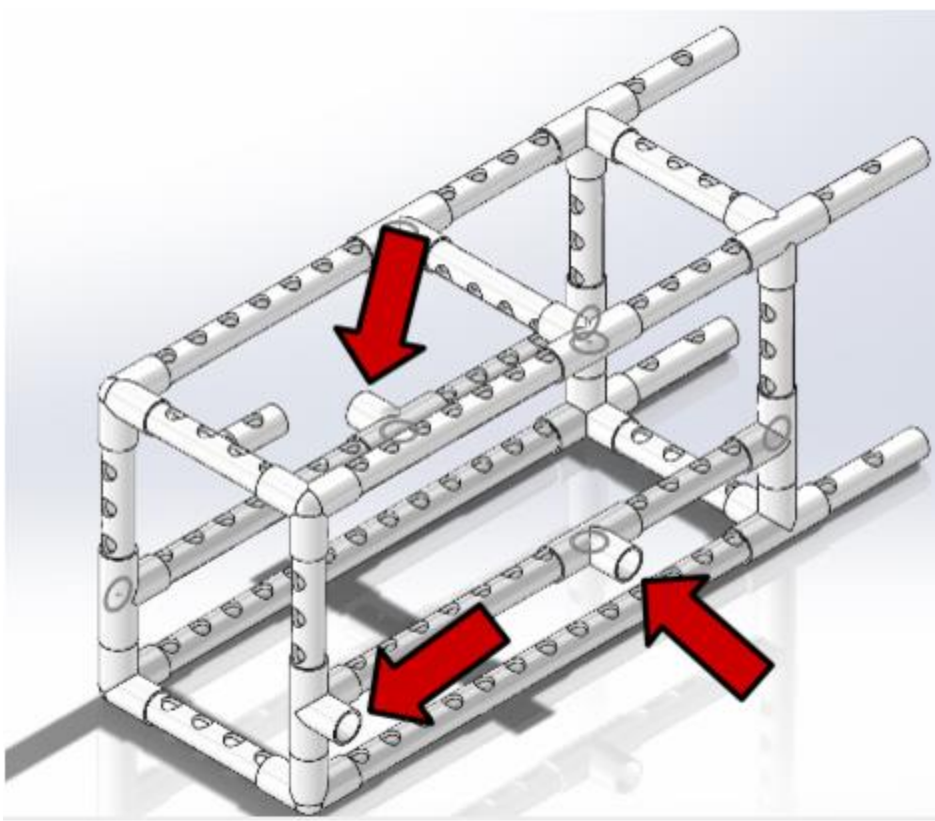
Appendix 9. *Dude* CAD perspective view



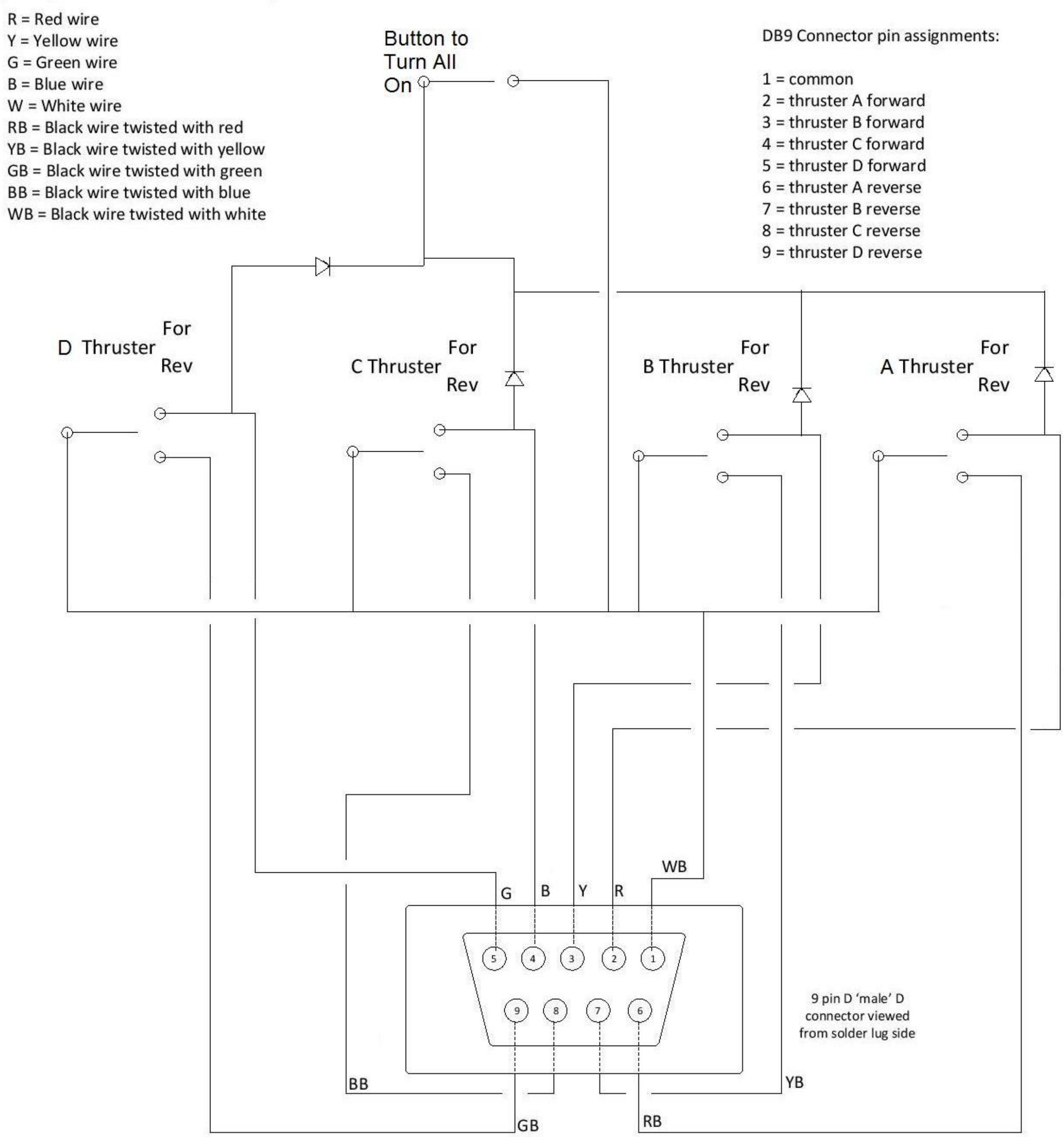
Appendix 10. *Ugli* CAD perspective view



Appendix 11. ROV frame with utility ports highlighted.



Appendix 12. Wiring Schematic



Appendix 13. Detailed mass budget.

Table 1. Detailed mass budget of the ROV.

Parts	Quantity *Dude*	Quantity *Ugli*	Mass (g) *Dude*	Mass (g) *Ugli*
Tee Joint	8	8	215.8	215.8
Shrouds	0	3	N/A	201.9
Horizontal PVC	4	4	175.8	175.8
Top Rear PVC	6	6	169.8	169.8
Bottom PVC	2	2	152.2	152.2
4 Way Corner	4	4	146.4	146.4
3 Way Corner	3	3	116.8	116.8
Mechanical Arm	0	1	N/A	112.7
Thruster Wing	0	2	N/A	160.0
Top Front PVC	4	4	111.6	111.6
Top Vertical PVC	4	4	100.0	100.0
Canister Support PVC	2	2	87.1	87.1
Thusters Protector PVC	4	4	78.5	78.5
5in length PVC with slots	2	2	58.6	58.6
Bottom Vertical PVC	4	4	36.8	36.8
Camera Connector	1	1	21.7	21.7
Thrusters	4	4	905.6	905.6
Canister	1	1	2916.9	2916.9
Battery	1	1	2512.5	2512.5
Camera	1	1	82.5	82.5
Water Bottles	5	5	374.5	374.5
Ballast	Water	Water	434.9	70.3
Zip Ties	33	38	17.8	20.5
Total	**-**	**-**	**10950.3**	**10963.0**

Appendix 14. Cost Calculations.

Item	Cost per Unit	Unit	Calculation Note	Amount	Cost
PVC					
2" Tubing	$1.88	per foot		1.25	$2.35
1/2" Tubing	$0.55	per foot		17.1	$9.41
Elbow	$0.30	ea		0	$0.00
Tee	$0.38	ea		7	$2.66
Cross	$1.16	ea		0	$0.00
3 Way Corner	$1.09	ea		4	$4.36
4 Way Corner	$1.33	ea		5	$6.65
135 degree	$0.99	ea		0	$0.00
PVC Cement	$0.03	per joint	each joint is one pipe going into the joint	53	$1.59
Buoyancy					$0.00
Floats	$4.99	ea		0	$0.00
Ping Pong Balls	$0.06	ea		0	$0.00
Pink Foam Board	$1.39	per sq foot		0	$0.00
Pool Noodle	$0.22	per inch		0	$0.00
Black Pipe Insulation	$1.32	per foot		0	$0.00
Library Water Bottles	$1.00	ea		5	$5.00
Control Box					
Black Box	$3.50	ea		1	$3.50
Toggle Switch	$1.49	ea		4	$5.96
Button	$1.09	ea		1	$1.09
Wire	$0.10	per foot		2	$0.20
DB9 Connector & Cable	$2.50	ea		1	$2.50
Diodes	$0.05	ea		4	$0.20
Solder	$0.00		complimentary	N/A	$0.00
Other					
Gray I-Beam	$0.15	ea		0	$0.00
Duct Tape	$0.10	per foot		2	$0.20
Bolts	$1.00	ea	for the bolt, nut, washer etc. all	4	$4.00

			included		
Hose Clamp	$1.70	ea		4	$6.80
Zip Tie	$0.10	ea	just for one setup	38	$3.80
Black Mesh	$0.62	per sq. foot		0	$0.00
Thrusters	$16.17	ea		4	$64.68
Servo	$4.00	ea		0	$0.00
Lead Weight	$18.00	per sq. foot			$0.00
Canister	$20.00			1	$20.00
Total Cost					**$124.95**

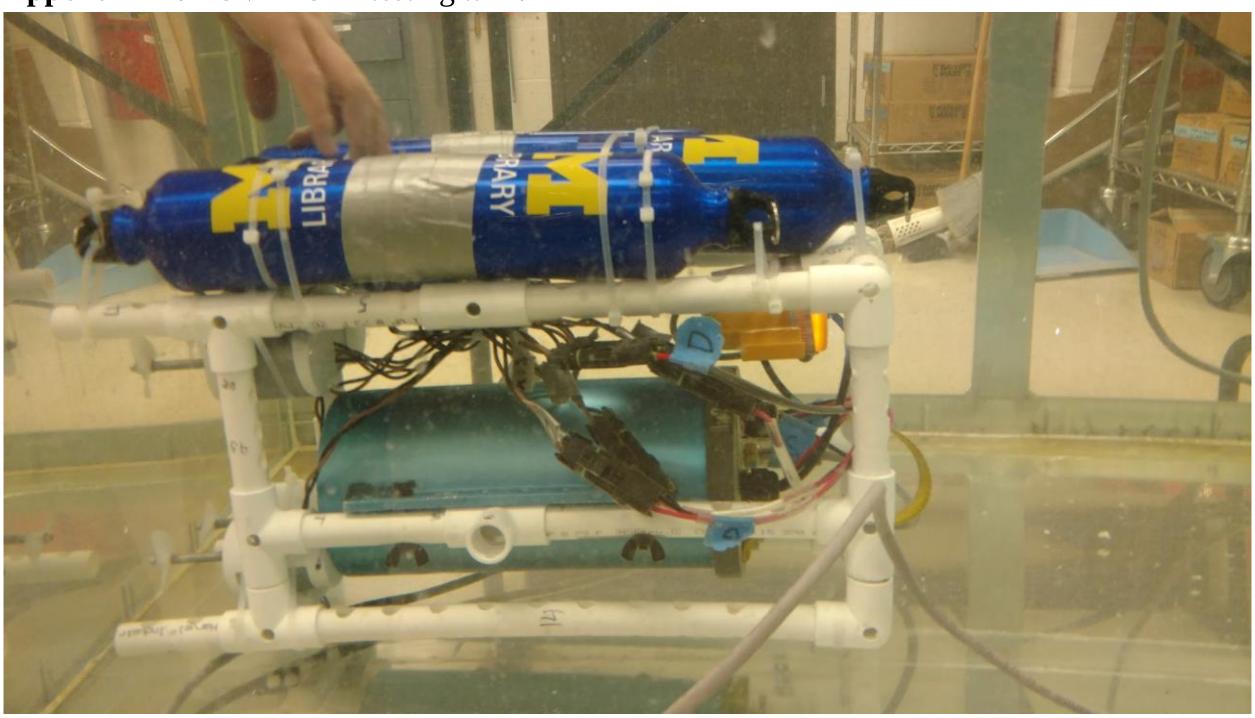
Appendix 15. Data from Thruster testing without Shroud.

		No Shroud					
		Forward			Reverse		
Thruster #	Load Cell Zero Load Reading (i.e. the offset) (V)	Load Cell Reading (V)	Battery Current (A)	Battery Voltage (V)	Load Cell Reading (V)	Battery Current (A)	Battery Voltage (V)
1	0.328	0.92	2.835	12.01	0.6	2.422	12.01
2	0.367	1.01	2.332	12.01	0.6	2.254	12.01
3*	0.326	1.14	2.912	12.01	0.636	2.671	12.01
4*	0.342	1.13	2.575	12.01	0.611	2.288	12.01
Average	0.341	1.05	2.664	12.01	0.612	2.409	12.01

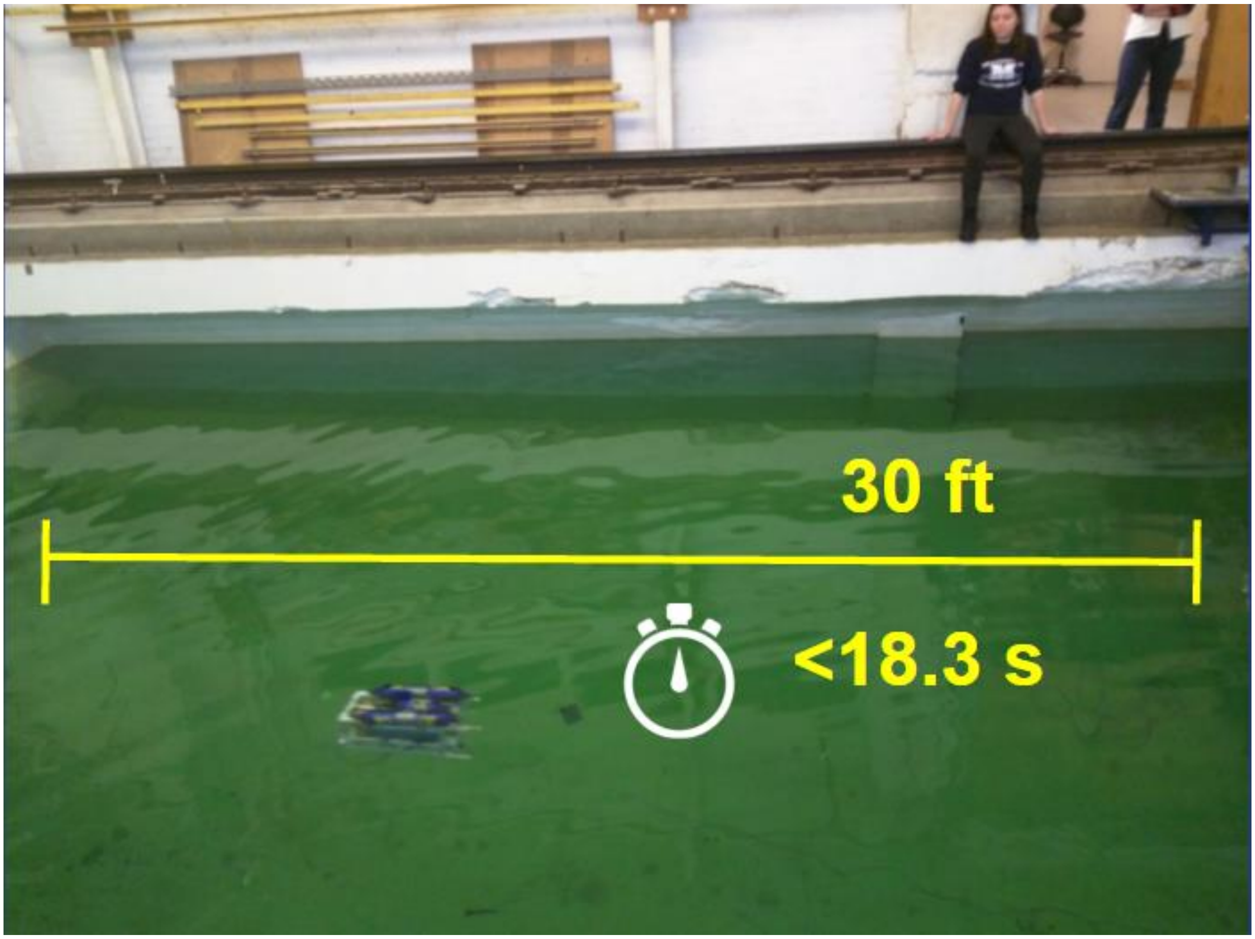
Appendix 16. Data from Thruster testing with Shroud.

		Shroud					
		Forward			Reverse		
Thruster #	Load Cell Zero Load Reading (i.e. the offset) (V)	Load Cell Reading (V)	Battery Current (A)	Battery Voltage (V)	Load Cell Reading (V)	Battery Current (A)	Battery Voltage (V)
1	0.328	1.02	2.728	12	0.601	2.334	12
2	0.367	1.04	2.405	12	0.602	2.163	12
3*	0.326	1.15	2.966	12	0.648	2.641	12
4*	0.342	1.15	2.575	12	0.576	2.268	12
Average	0.341	1.09	2.669	12	0.607	2.352	12

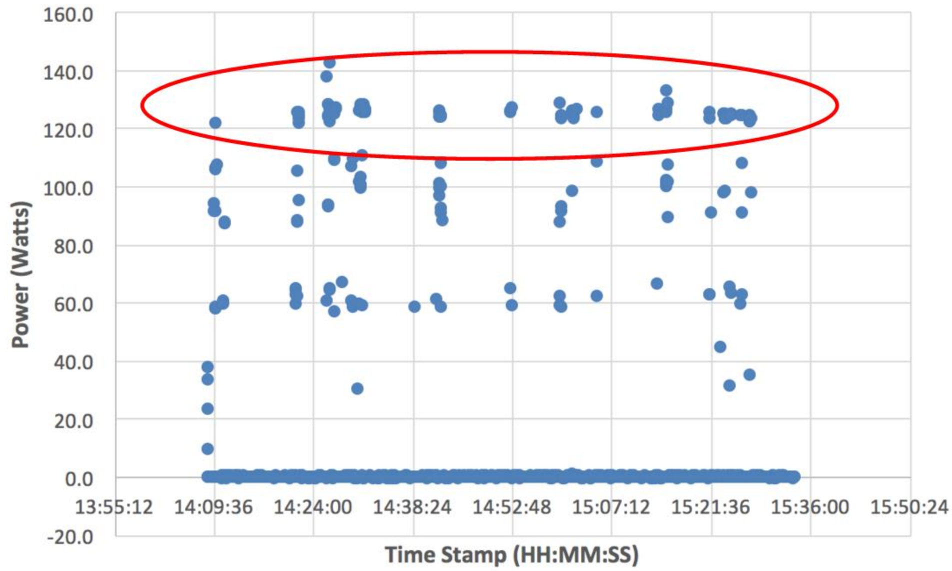
Appendix 17. ROV in GFL testing tank.



Appendix 18. MHL speed test procedure. The ROV must travel a distance of 30 ft in the tank in at least 18.3 seconds, in order to achieve the minimum velocity of 0.5 m/s



Appendix 19. MHL testing data used to determine braking power



Appendix 20. Maneuverability Competition Results

Trial	Time (min)
1	2:55
2*	**2:49**
3	2:55
Average	**2:53**

Appendix 21. Full Scale Power Calculations.
First calculate scaled thrust, T, using the drag equation:

$$T = C_D \frac{1}{2} \rho A_{ROV} V^2$$

where C_D is the actual coefficient of drag: 1.421; ρ is the density of salt water at 10°C: 1030 kg/m^3; A_{ROV} is the full scale cross-sectional area of the front of the ROV: 0.248 m^2, and V is the full scale velocity: 0.426 m/s. From this equation, the full scale thrust is calculated to be 65.87 N.

Using the full scale thrust, full scale effective power, P_E, can be determined using the following equations:

$$P_E = R_T V$$
$$P_E = TV$$

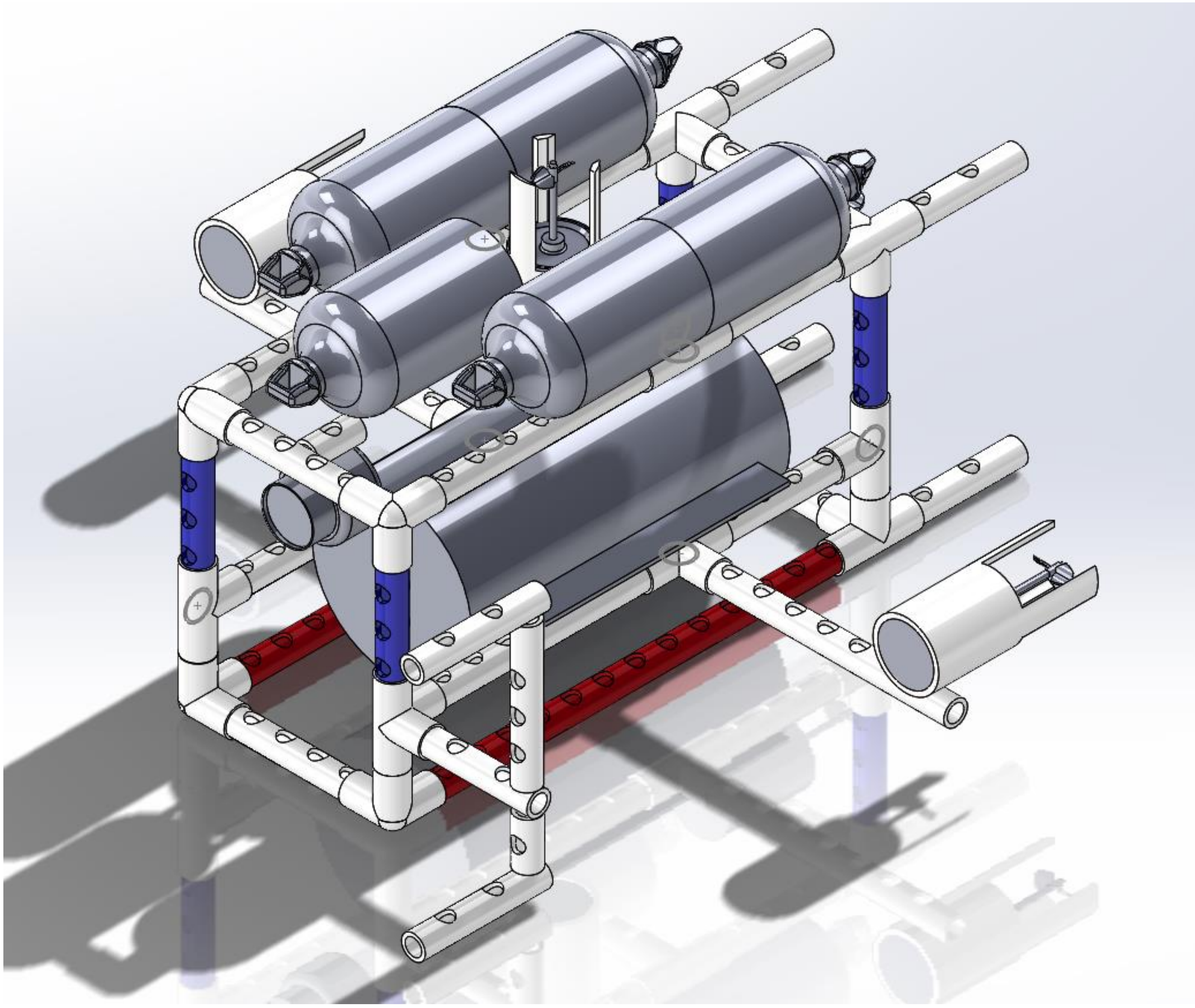
where R_T is total resistance, which can be approximated by T, thrust: 65.87 N; and V is full scale velocity: 0.426 m/s. The full scale effective power is calculated to be 28.06 W.

Using the full scale effective power, the hydrodynamic efficiency equation below can be used to calculate the ROV's full scale braking power, P_B which is the total power needed to operate the full scale ROV.

$$\eta = \frac{P_E}{P_B}$$

Here η is the hydrodynamic efficiency: 0.137; and P_E is the full scale effective power: 28.06. Thus braking power is calculated as 204.82 W.

Appendix 22. Structural changes to the full scale ROV. Tubes that can be shortened are colored blue, and the pieces that are unnecessary to the structure are colored red.



The ROV is operated using a control box that is connected to the thrusters by a tether. Each thruster is controlled by a separate toggle to allow the thrusters to propel both forwards and backwards. An additional button moves all the thrusters forward for ease of control.