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Abstract

Last summer, the explosion at the Deepwater Horizon Oil Rig devastated the Gulf of Mexico and shocked environmentalists around the world. Early attempts to stem the flow of oil into the Gulf involved using Remote Operated Vehicles (ROVs) to close the blowout preventing valves. These efforts were largely futile, and the well was not fully capped until September, a full 5 months after the initial explosion. This disaster highlighted the need to develop new ROVs in preparation for future catastrophes. The Sidwell Friends Robotics Team aims to demonstrate the ROV's ability to complete a number of tasks related to disaster mitigation and evaluation. Figure 1 shows our lightweight, compact ROV (codenamed *N.A.R.W.H.A.L.*), which uses two cameras, four bilge motors, and one Tetrix motor to navigate and interact with its underwater environment. In addition, *N.A.R.W.H.A.L.* is equipped with a pressure sensor to measure depth, a suction tube to collect water samples, and three sticky rat traps to pick up animal samples and transport them to the surface. *N.A.R.W.H.A.L.* is controlled using a Logitech II Joystick Controller navigated through a Lego NXT Brick and programmed with RobotC. During the competition we will demonstrate the utility of our design by quickly and effectively completing the challenges with which we are presented.

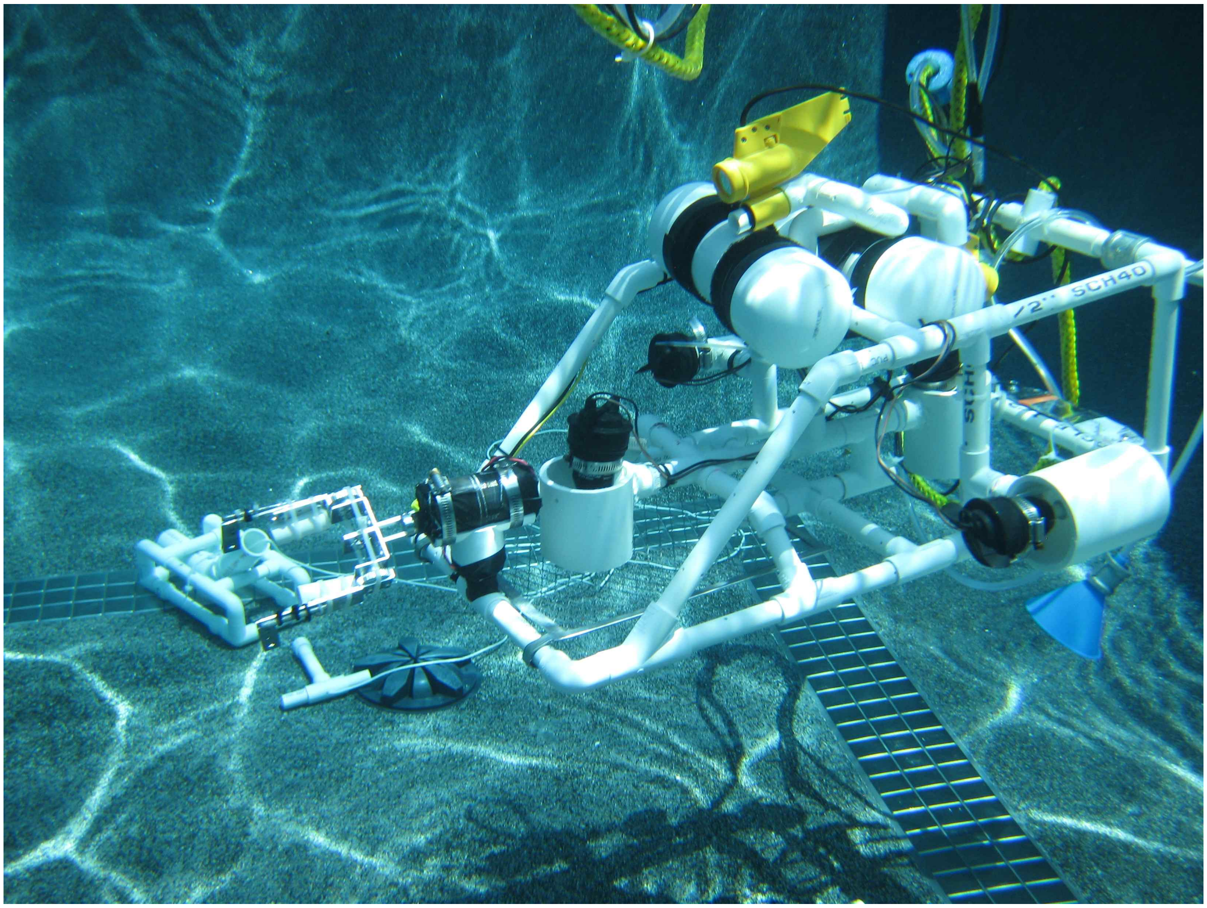


Figure 1: The completed ROV in action

Design Rationale – Vehicle Systems

Rotational Manipulator

After a great deal of planning and extensive exploration of a number of potential solutions, we created a wheel-turning manipulator. Originally, we thought we could have a claw that would grab the edge of the wheel and then spin around an imaginary axis at the wheel's center. Soon after considering this idea, however, we realized that it would be more efficient to put a two-pronged claw inside the wheel and spin it around the center axis. We used Tetrix pieces to build the frame for this design. At first, we considered using a bilge pump motor similar to the ones that propel our robot's motion, but our testing revealed that a bilge pump motor did not provide enough torque to spin the wheel. Instead, we used a waterproofed Tetrix 12-volt DC motor, which provides more torque than the bilge pump motor. To protect the motor, we made a waterproof casing using a 3D printer. Next, we drilled two holes in the casing, one for the wires and one for the motor shaft. We installed the motor, sealed the openings, and covered the entire casing in waterproof tape. As a last precaution against water leakage, we put Vaseline in the hole that held the shaft and silicon in the wire hole.

At this point, we had a very efficient mechanism to turn the wheel, but we still needed manipulators to complete many of the other tasks. Rather than design an entirely new system, we altered the wheel-turning mechanism so that it was effective in completing a greater variety of challenges. As Figure 2 shows, we attached two 1-inch long pieces of Tetrix metal at right angles on the tips of the wheel manipulator. With this addition, the wheel manipulator could be used as a hook to detach the Velcro and lift and place the well-head cap. The reason we have two hooks rather than one, on the device, is to enable us to pick up and place the kill-switch.

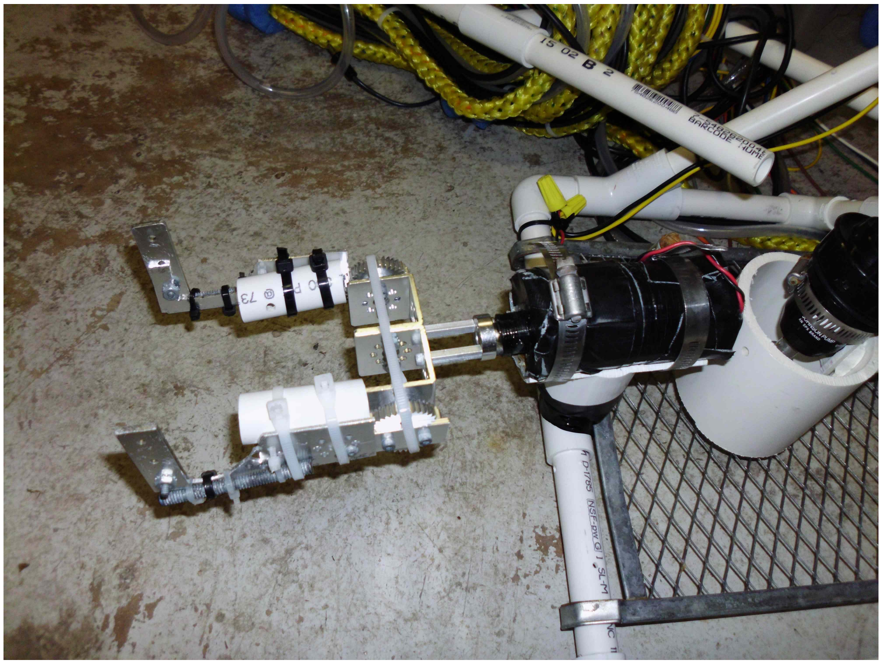


Figure 2: Final rotational manipulator

Pressure Sensor

In order to properly obtain a water sample, we needed to develop a system to measure depth. After some effort, we succeeded in creating a water pressure sensor with real-time data accessible from the control station. This enabled us to access the pressure readings without wasting valuable camera space. As seen in Figure 3, the sensor includes a Vernier Gas Pressure Sensor, which collects data through a Vernier LabQuest, which connects to a vinyl tube with an open-ended bottle at the bottom (Figure 4). This bottle is attached to the robot, and the open end allows for the compression of the gas in the system, which is caused by the increase in water pressure as the robot descends. The increase in pressure at any given depth is given by the equation: $P = \rho_{water} * g * h$. h represents the depth of the robot, g represents the acceleration due to gravity (9.81m/s^2), and ρ_{water} is 1000kg/m^3 at 5ºC. This equation permits us to roughly predict the depth from the pressure reading. As the robot descends, the pressure should increase at a rate of roughly 9.81 kPa per meter. This system relies on most of the volume of the gas in the system being at the same depth as the robot, which we achieved by having a 250 mL bottle on the robot and attaching flotation material to the tube to force it to go directly upward from the robot to the surface and get the most accurate depth reading.

Figure 3: The Vernier Gas Pressure Sensor and LabQuest.

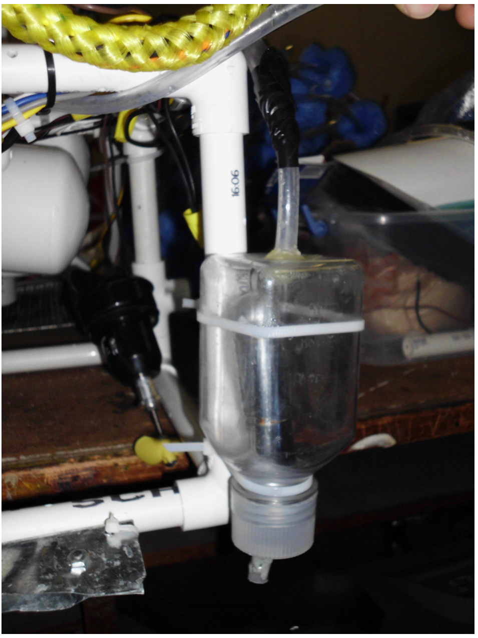


Figure 4: The 250 mL tube attached to the robot with a weight inside to ensure neutral buoyancy

Water Sample Collector

In order to collect an undiluted water sample, we use the difference between the pressure underwater and the pressure at the surface to our advantage. A tube attached to the robot stretches the length of the tether and contains a long stiff polycarbonate tube which the ROV inserts into the water sample bucket. The entire system is filled with air during the robot's descent, and, as seen in Figure 5, a bike pump is attached to the tube in order to clear the tube of any pool water prior to the sample collection. The tube is inserted into the pipe in the water bucket and a valve at the controller's end of the tube is opened. The underwater pressure is much greater than it is at the other end, so water travels up the tube to restore equilibrium. As seen in Figure 6, a funnel is attached at the end of the tube in order to make inserting the tube into the tank easier for our drivers. By helping locate the tank's protruding tube, the funnel makes feeding water into the sampling device a quicker process.

Figure 5: The bike pump attached to the end of the tube

Figure 6: The funnel is placed at the end of the tube to ease collection of the water sample

Rat Traps

To pick up the biological samples, we decided to go with a very simple approach. Sticky rat traps are used on the bottom of our robot in order to pick up the biological samples on the platforms. The rat traps work very well underwater and are simple to attach to the robot. Zip ties run from holes drilled in the rat traps to the meshing at the front of the robot to ensure they stay secure. The mesh is large enough to hold three rat traps, which enables the ROV to pick up each of the three biological samples. Although the traps are sticky and frustrating to work with, they are definitely the simplest, and most efficient method we could find for the task.

Although this was our final solution, we initially attempted to collect the biological samples with a claw that would snap them up, similar to a mouth. Although we managed to get this claw to work, we realized that it was an inefficient way to collect the samples. Though this was a perfectly viable option, it used a motor that was not necessary otherwise and was not as reliable as the rat traps, which are a far simpler method.

Carabiner Mount

To detach the riser pipe from the oil well, our ROV uses a carabiner attached to a rope. The carabiner's spring is removed so it doesn't lock, turning it into more of a hook. Initially, the carabiner is mounted to the robot by a thin piece of sheet metal folded in half to make a makeshift clamp. The metal clamp is securely bound to the robot by two screws and zip ties. Our ROV then navigates to the U-bolt on the riser pipe and hooks the carabiner to it. When the robot pulls away, the carabiner and rope unit separates, as it is only attached by the loose metal mount. The team can then use the rope to remove the riser pipe from the oil well from land, while the ROV continues onto other tasks.

Design Rationale – Robot Control and Propulsion

Propulsion System

Our robot features two longitudinal motors and two vertical motors. Each of the propulsion motors is a 12-volt Johnson brand 500 gph bilge-pump motor wired directly through our tether to our control box. Fortunately, it wasn't necessary to waterproof any of the motors. Each motor has a plastic propeller attached to its end, giving the robot adequate propulsion to complete the required tasks. Our longitudinal motors are situated on the port and starboard sides of the robot. This way, if we spin the motors in the same direction, we can create forward or backward motion on the horizontal axis. To turn the robot, we can spin the propellers in opposite directions or spin only one at a time. The motors we use for vertical motion point straight down. By spinning them in the same direction, we create up or down motion, and by spinning them in opposite directions, we can angle the front of the robot up or down, allowing us to perform such tasks as fastening the wellhead cap on the oil well.

Wiring Schematic

Our tether consists of 15 meters of 10 copper wires, two camera cables, and a ¾-inch diameter flexible plastic tubing. We put pieces of foam approximately every meter to keep the tether neutrally buoyant. The 10 copper wires are attached to the motors that are used for motion and turning the manipulator. The two camera cables are hooked to monitors on the surface, and the flexible plastic tubing is used to collect the sample of red water. As seen in Figure 7, our ROV's wiring schematic, our control box includes three HiTechnic DC Motor Controllers and one Lego Mindstorms NXT Intelligent Brick. Each motor controller has outputs for two motors and two slots for the power source so that the controllers can be hooked up in series. Initially, we only had on and off switches controlling the robot, but using the motor controllers allowed us to regulate power and use a gamepad to control the robot. These controllers provide better control of the robot and enable us to do some of the tasks that require fine positioning and movement. As seen in Figure 7, we have a 20-amp fuse in addition to an on-off switch, allowing us ensure the safety of those handling the robot. In addition to these safety measures, we also waterproofed all of our wire nuts with silicone to prevent harming anybody who might be in the water with the ROV.

Control Scheme

We opted to control our ROV via a Lego Mindstorms Intelligent NXT Brick and Tetrix HiTechnic Motor Controllers.. We chose this partially due to our previous experience with this system and partially for ease of design and implementation. Another factor that facilitated this decision was that we were fortunate to be in possession of all the necessary parts to implement this system. Both the HiTechnic Motor Controllers and the Intelligent NXT Brick are among the most expensive pieces of equipment that we use in conjunction with our ROV. A detailed list of expenses can be found in Appendix A.

All of the wiring from our ROV plugs into a trio of HiTechnic DC Motor Controllers, each of which has two output ports, which can individually supply up to 12 volts of power. These controllers are in turn wired to a Lego Mindstorms Intelligent NXT Brick. The brick is plugged into a laptop running the RobotC software used to program the ROV controls. Direct input to the motors is achieved using a Logitech II Joystick Controller. The control scheme, as seen in Figure 10, is as follows: The left and right joysticks are mapped to the port and starboard motors, respectively (see Figure 8). This is done to allow variable input- pushing the joystick halfway forward provides less power than pushing it all the way. As seen in Figure 9, our fore and aft vertical motors are mapped to the controller's shoulder buttons. The left and right shoulder buttons control the forward and back motors, respectively. In each case, pressing the upper button causes the motor to push the ROV up while the lower button pushes the ROV down. With regards to vertical motion, variable power is unnecessary, so each button provides maximum power. Finally, our rotational manipulator is controlled by buttons 1 and 3 on the right side of the control; 1 spins it counterclockwise and 3 spins it clockwise relative to the camera's view.

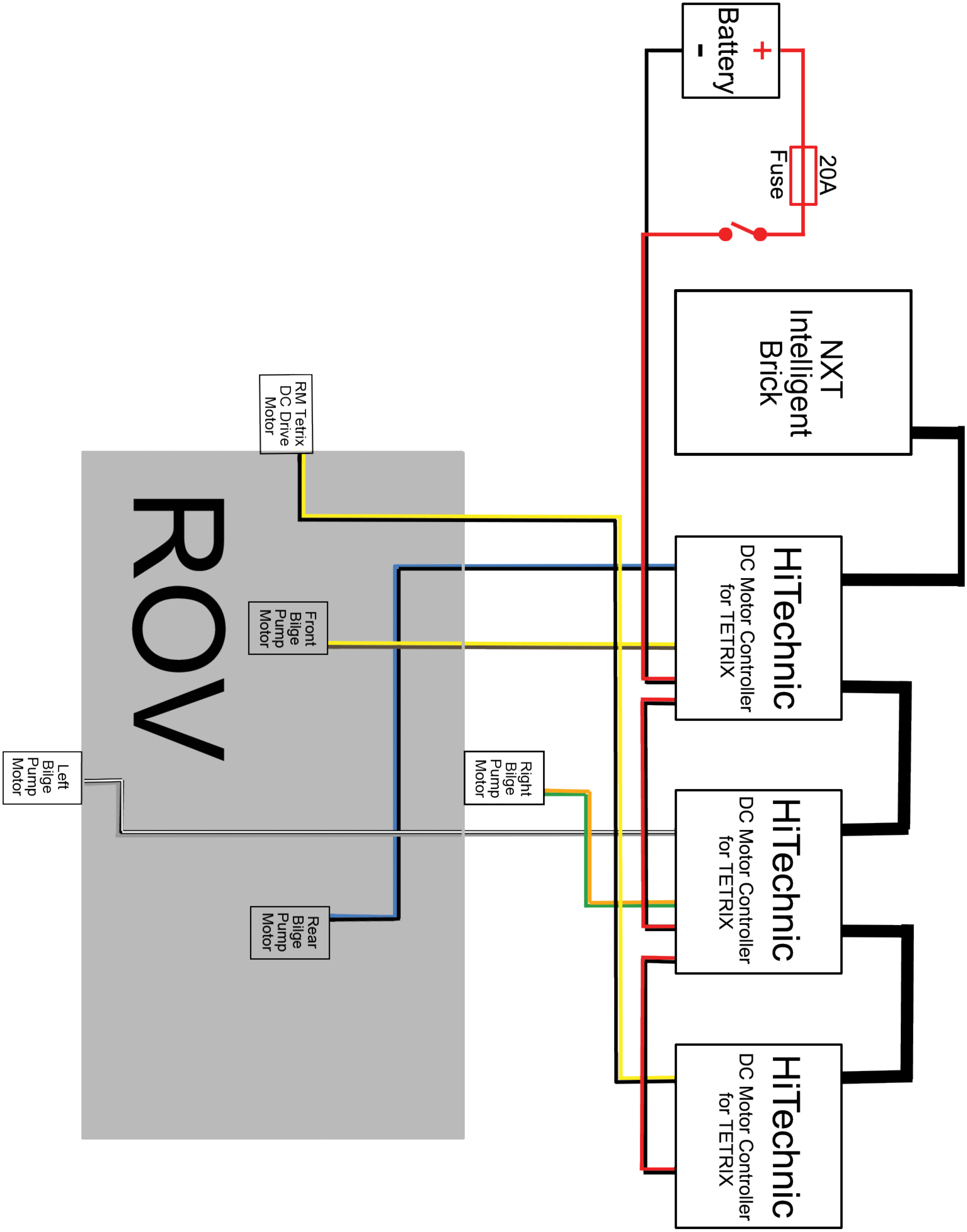


Figure 7: Our ROV's Wiring Schematic

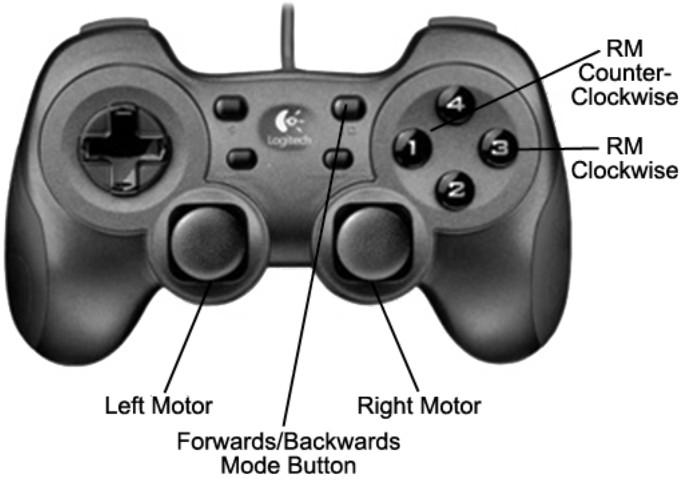


Figure 8: Top view of the control scheme

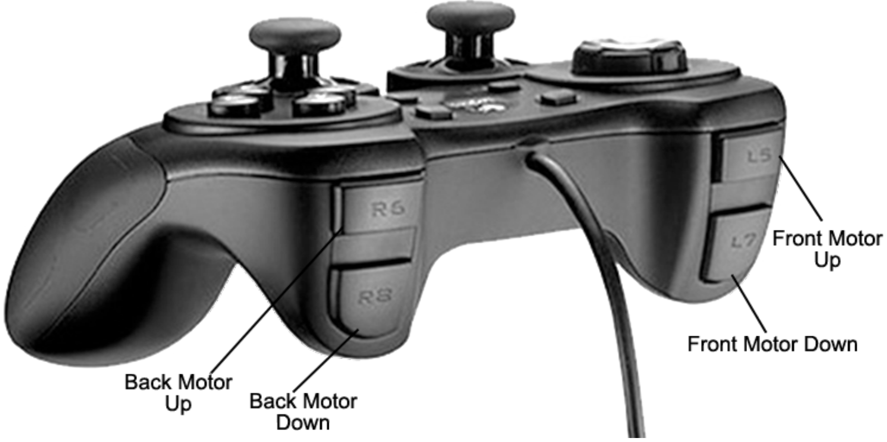
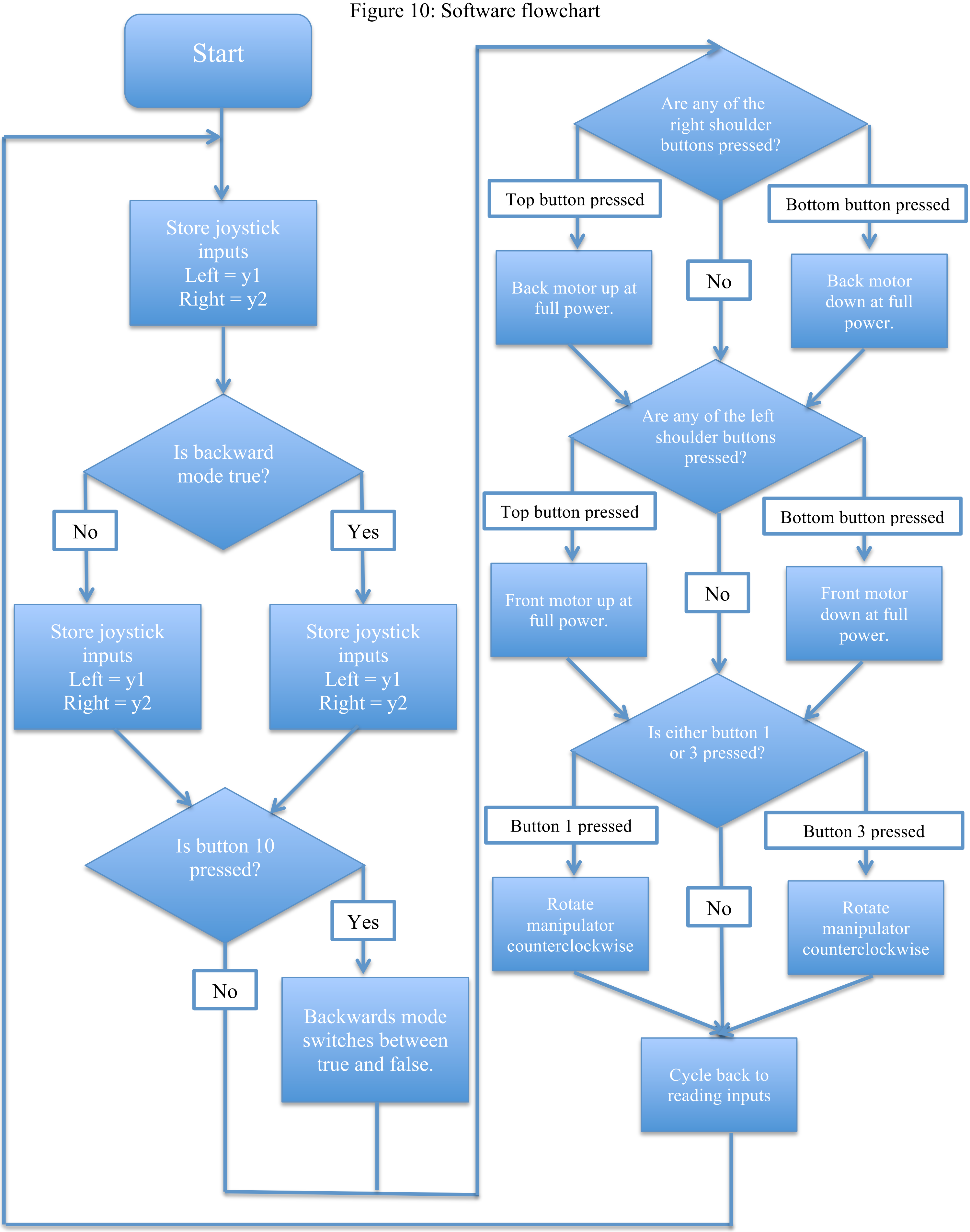


Figure 9: Front view of the control scheme

Figure 10: Software flowchart



Buoyancy

The primary challenge when dealing with buoyancy was not creating a neutrally buoyant robot, but creating one that would be able to handle the changes in weight that our robot had to undergo during the challenge. Over the course of the challenge, the wellhead cap, collected water samples, and even the small biological samples add weight to our ROV, making our robot less buoyant as it goes through the challenges. Consequently, we needed to find a balance where our robot was slightly positively buoyant to begin with, and slightly negatively buoyant at its heaviest, once it has the wellhead cap.

Our frame is made of PVC pipe with several small holes in it to allowing the air to evacuate. If the pipes had too few holes, the buoyancy would change each time we put it in the water because pockets of air would get trapped. The best course of action, therefore, was to make the pipes fill up as quickly as possible with water, so that we could get to our challenges with maximum efficiency. However, between the water-filled frame and the functioning pieces, our robot wasn't buoyant enough. To compensate, we added large, sealed tanks made of PVC pipe, creating enough buoyancy to counterbalance to weight of the rest of the robot. Additionally, our heavy manipulating device made the robot tip forward, even when neutrally buoyant. To balance the robot, we added weights to the back, making the two halves roughly equal in weight. The result of all these components is a robot that is balanced and roughly neutrally buoyant with the ability to handle the inherent changes in buoyancy that come with completing the challenges of the competition.

Difficulties

Buoyancy

Attaining neutral buoyancy was problematic because we had to adjust the buoyancy each time something was added to the robot. The most difficult addition was the suction tank, which was also a small buoyancy tank. We solved this problem by placing a weight in the tank. Additionally, we started with only two non-adjustable buoyancy tanks, filled with air, which were hard to attach. Further trouble occurred when the buoyancy varied from day to day and pool to pool. When tested in our small pool (5ft diameter x 3ft depth), the robot appeared to be overly buoyant, so we increased the amount of weight on the back. When testing in a full size pool, however, the robot sank even after the removal of the weight we had added the previous day. We then added a third, smaller buoyancy tank. This system worked until the tanks filled with water, forcing us to reseal the tanks.

Wiring

Our first control box did not go as well as we planned. We hooked up the motors in series to on-off switches and had a great deal of trouble configuring the wiring in a small black box. The wires would regularly uncrimp and create faulty connections. We also could not control the power to the motors and had a lot of difficulty doing any of the challenges that required precision. However, when we switched to motor controllers, we were able to use a larger control box, and wiring was no longer a problem. We were also able to make any changes to direction of the motors in our RobotC code rather than having to rewire the entire system.

Suction

Unlike the ROV's other attachments, we didn't have any trouble implementing our idea to suction the water; the trouble came earlier, when initially brainstorming how to approach the task. Our first idea involved syringes with motors pulling the plungers. This idea was scrapped due to the high torque required to pull the plunger. Our next idea included a container to collect the sample in, but this also proved ineffective. When the robot was descending, the container filled with air and provided extra buoyancy, making it more difficult to descend. When the robot sucked up the sample, the container filled with water and prevented the robot from surfacing. We solved this by just using the tube without a container, which reduced the changes in buoyancy that had been so problematic.

Pressure Sensor

Creating an accurate pressure sensor proved to be a challenging task. Initially, we thought of using a depth sensor usually used for scuba diving mounted on our ROV within view of our underwater camera. These sensors, however, were difficult to obtain, expensive, and too imprecise for use in the competition. Instead, we measured the water pressure with a gas pressure gauge.

Safety

In order to both ensure the safety of the people working on the robot and to protect the propellers, we needed to encase the motors. At first, we used metal meshing because it allowed water to easily flow through without allowing debris or elements of the testing course to touch the motor. The metal meshing was functional, but it was hard to shape effectively, because we had to be wary of the material's sharp edges. Additionally, a collision could force the metal mesh into the very propeller it was designed to protect. To address this issue, we used a more sturdy material for our casing: PVC pipe. As long as we kept the area directly behind the motors clear, we avoided losing power and the motors remained excellently protected. A model of these casings can be seen in the CAD images in Appendix C.

When we wired the robot, we made sure to include both a fuse and a circuit breaker in our control box. We included a simple on-off switch that controls all the power to the motor controllers and installed a 20-amp fuse to protect against power surges.

Additionally, our team made sure to put all the open electrical equipment in a waterproof box. Similarly, all of the connections on our robot were thoroughly waterproofed with silicone and were tested for leakage. We made sure that all the sharp metal and plastic edges were filed down so that the robot was safe to handle.

Lastly, whenever anyone on the team was using power tools or was cutting pipe, we self-enforced the team rule that safety goggles and any other appropriate safety equipment must be worn.

Troubleshooting Techniques

We had different ways to troubleshoot all the systems on our robot. For the motors and electrical systems, we mainly used a voltmeter. For example, if our left motor was moving more slowly than our right one, we used the voltmeter to see if any connections were faulty before we replaced the motor itself. For our attachments, we simply used logic and repeated testing to troubleshoot. At first when we were making the manipulator, the tongs were too close together which made it hard for us to fit them in the wheel. To address this issue, we adjusted the spacing between the tongs and revised our robot model. To troubleshoot buoyancy issues, we would adjust weight in the appropriate places. For example, if the robot was too buoyant on once side, we would at ballast to that side.

Ideas for Future Improvement

If we had had more time to prepare, we could have improved our front manipulator. We chose to make a more generally capable tool rather than several specialized tools for specific functions. We might have considered adding a second manipulator consisting of two parallel hooks (like our current front manipulator), but which would not rotate, making it ideal for lifting the T and removing the Velcro from the pipe. We would then redesign our current front manipulator to more closely resemble a tuning fork rotating on an axis, making it optimal for turning the wheel.

Additionally, had we known the limits of our bilge pump motors, we would have added two more vertical motors to our design, one fore and one aft. Our current vertical motors only barely provide the necessary power to the surface, so adding the additional thrust would increase both the movement capabilities of the robot and its ability to rise uniformly without tilting.

Lessons Learned

We learned valuable lessons from the many hours we spent building and improving our robot. No one on our team had any experience with underwater robotics, so everything from control flow to aquatic propulsion to tether management was completely new to us. In addition, we learned quite a few things about working together as a team. For example, we realized that more people working on one thing is not always more efficient. We often had too many people focused on one task, which reduced efficiency and caused conflict. Additionally, we learned the importance of teamwork, not just within our own team, but also with the other team from Sidwell. We had some suggestions for fixing problems the other team was having and visa versa. Finally, we learned just how much work is required to create a functioning ROV and manage the logistics of a big team.

Teamwork

Because this was our school's first year designing an underwater robot, there was no preexisting hierarchy for our team to follow. Our first meeting took place in late February, in which we read through the tasks our ROV would need to complete. Given the size of our team, we felt it would be more productive if we split into smaller groups to discuss how we could complete each individual task. Since we had never built a ROV, we felt it was also necessary to conduct some background research in building them. After assigning ourselves to different tasks based on each individual's strengths and interests we divided into groups and conducted research relating to our group's task. A complete list of groups can be found in Appendix B, in addition to a schedule detailing when we worked on each part of the process, which can be found in Figure 11 below.

After conducting individual group research, the entire team came together to discuss the robot's general design to ensure that we had a cohesive plan. We continued to work in this fashion throughout the process; that is, we continued to work in smaller groups and then present our ideas to the entire team. These small groups helped create and strengthen friendships throughout the team, which in turn helped create a friendly environment in our robotics lab. Although most tasks were done by small groups, some tasks were done by the group as a whole, such as making our robot neutrally buoyant and creating the tether, as well as creating and designing the robot's frame. A combination of all of these things helped all of us come together as a team, making it an enjoyable and fun experience for everyone.

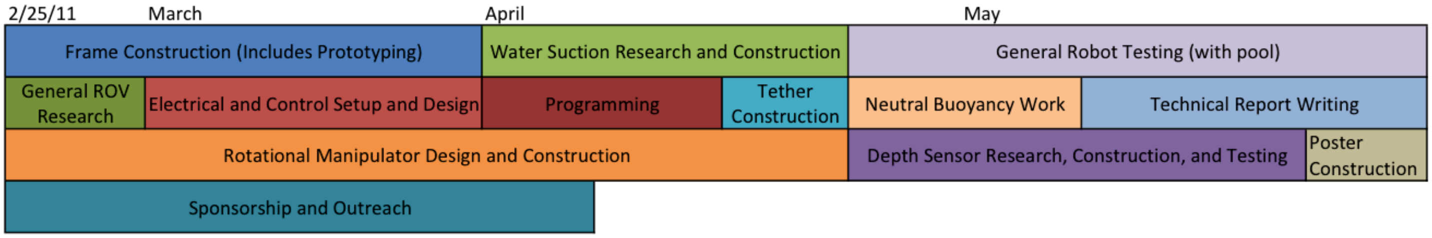


Figure 11: The team's schedule of building the ROV and completing the accompanying materials.

Reflections

Cecilia Auerswald:

When the team first came together in February, we were a group of independent, somewhat confused students. Over the past couple months we have learned to come together, collaborate, combine ideas, and delegate tasks. Since this is our school's first year hosting a robotics team few of us had previous experience with robotics. We started out scattered, unsure what to do or how to do it. However, over time we came to realize that there were two things to remember: talk to your team and work hard. This year was my first year working on a robotics team. I walked into the robotics lab with another member, and started watching people conceptualize and build the robot. I had considered joining the team at the very beginning when they had announced to the school that they needed members, but I had decided not to, figuring that it would just suck up time and I wouldn't be very good at it. While hanging out with the people working in the lab, however, I started doing odd jobs, finding drill bits and holding electrical tape. There were familiar faces in the room, and I began asking questions about what they were doing (perhaps bothering them).

After asking questions, observing, and helping out on that first day, before long I was attending weekly meetings and spending free periods putting together motors. I had been somewhat correct on one point; for the first couple weeks, I had no idea what I was doing. Everyone was very helpful, though, in familiarizing me with the tools and design of the robot.

By continuing to do my best helping out, I became comfortable working with the robot, and more and more excited about the competition. Now I really enjoy coming to the lab and working out kinks; I see problems with the robot, not as a problem but as a challenge. I've gained useful technical skills and an exciting new interest. Working with my friends, old and new, to make our robot has also taught me things that I will be able to apply for the rest of my life. The creativity of my teammates was another thing that made working on the team fun. They worked hard on the robot, and were able to stay optimistic and engaged even when things didn't work out the way we planned. As the competition approaches this year, I am extremely glad that I walked into the room that first day, and look forward to working on a robot for the competition again next year.

Danny Baker:

Looking back, I am extremely proud of not only our final robot, but also the effort that we exerted, teamwork that we displayed, and leadership that was exhibited by each and every member of our team. Although at several points we faced both challenges with the robot itself and conflict between team members our team came together, collaborating to create the robot. However, both the challenges we faced with the robot and the disputes we had between team members caused us to have both a better robot and stronger team. With team members as passionate and enthusiastic about our robot as we had, it was only natural that several arguments broke out regarding its design. And every challenge that we faced, although frustrating, ended up being a learning experience, helping us create a better robot. Overall, I believe that even if we don't have the best robot in the competition, we will still have one of the most cohesive teams.

Acknowledgements

It being our inaugural year, our club would not have survived without support and mentoring from our teachers and parents. Foremost, our club would not have even existed without the unyielding determination of our coach and teacher, Darby Thompson. She is a new computer science teacher at Sidwell and immediately began invoking a passion for robotics and engineering in the student population.

We would like to thank the Brown family. They not only supplied us with unfettered access to their pool for practice, but also donated materials for us to work with. We would also like to thank our school, Sidwell Friends, and our principal, Mrs. Palmer. They provided a large space on campus to design and build our robot, which allowed our team to easily meet even on weekdays. In addition, we would like to thank our school's science department, particularly Mrs. Wooden and Mr. Donley, for trusting us with their expensive Vernier Gas Pressure Sensor and Vernier LabQuest equipment. We would also like to thank SolidWorks Corp. for donating their CAD software to our team. Finally, we need to thank our sponsors: Papa John's Pizza for giving us significant discounts on team pizza orders, as well as Aurora Flight Sciences and the Central Children's Charities for their support and funding of the club. We hope we can continue a relationship between these companies and our club in the years to come.

Appendix A - Expense Sheet

Bulk Materials

Part #	Unit	Item	Supplier	Cost Per	Quantity	Item Cost	Our Cost
	pkg/500	GB 50098 Electrical Assorted Cable Ties, 500	Home Depot	$21.72	1	$21.72	$21.72
	Each	PVC 2-way 45 degree joint, 1/2"	Home Depot	$0.27	4	$1.08	$1.08
	Each	PVC 2-way 90 degree coiner joint, 1/2"	Home Depot	$1.08	11	$11.88	$11.88
	Each	PVC 3-way 45 degree joint, 1/2"	Home Depot	$0.30	2	$0.60	$0.60
	Each	PVC 3-way corner joint, 1/2"	Home Depot	$0.46	4	$1.84	$1.84
	Each	PVC 4-way joint, 1/2"	Home Depot	$0.50	4	$2.00	$2.00
	Each	PVC Pipe, 1" diameter, 16'	Home Depot	$7.99	1	$7.99	$7.99
	Each	PVC Pipe, 2" diameter, 1/2'	Home Depot	$1.00	1	$1.00	$1.00
	Each	PVC Pipe, 3" diameter, 3'	Home Depot	$2.99	1	$2.99	$2.99
	Each	PVC T joints, 1/2"	Home Depot	$0.20	19	$3.80	$3.80
					Total		**$54.90**

Propulsion System

Part #	Unit	Item	Supplier	Cost Per	Quantity	Item Cost	Our Cost
B0006095V0	Each	550 Propeller Adapter, direct drive	Amazon	$4.11	4	$16.44	$16.44
28552	Each	Bilge Pro Replacement Motor Cartridge for 500gph Pumps	West Marine	$19.99	4	$79.96	$79.96
OC1250	Each	Octura 1250 Plastic Propeller	Amazon	$2.89	4	$11.56	$11.56
					Total		**$107.96**

Rotational Manipulator

Part #	Unit	Item	Supplier	Cost Per	Quantity	Item Cost	Our Cost
W739088	pkg/6	Tetrix 100 mm Axles	Lego Education Store	$17.95	1	$2.99	$2.99
W739172	pkg/2	Tetrix Axle Hub	Lego Education Store	$7.95	3	$11.93	$11.93
W739065	pkg/2	Tetrix Channels (32 mm)	Lego Education Store	$11.95	1	$5.98	$5.98
W739083	Each	Tetrix DC Drive Motor	Existing	$52.99	1	$52.99	$0.00
W739070	pkg/2	Tetrix Flat Bars	Lego Education Store	$10.95	1	$5.48	$5.48
W739073	pkg/2	Tetrix Flat Building Plate	Lego Education Store	$14.95	1	$7.48	$7.48
W739028	pkg/2	Tetrix Gears (40 tooth)	Lego Education Store	$24.95	2	$24.95	$24.95
W739102	pkg/12	Tetrix Stand-Off Posts (1")	Lego Education Store	$3.95	2	$0.66	$0.66
					Total		**$59.45**

Other Attachments

Part #	Unit	Item	Supplier	Cost Per	Quantity	Item Cost	Our Cost
	Each	3/8" vinyl tubing, 100'	Ace Hardware	$25	1	$25.00	$25.00
	Each	Funnel	Giant Food	$2.74	1	$2.74	$2.74
196223	Each	MD Building Products 3'X3' Plain Aluminum Sheet	Home Depot	$8.97	1	$8.97	$8.97
	Each	Medium metal clamps	Home Depot	$1.09	6	$6.54	$6.54
	Each	Metal weights (steel pipe couplings)	Home Depot	$1.35	2	$2.70	$2.70
	Each	Oil Siphon	Walmart	$7.99	1	$7.99	$7.99
	Each	Paint tray metal mesh holder	Home Depot	$3.50	1	$3.50	$3.50
74770	pkg/2	Stick-Em Rat and Mouse Trap	Ace Hardware	$6.49	5	$32.45	$32.45
	Each	Stiff plastic 3/8" tubing, 2'	Home Depot	$1.20	1	$1.20	$1.20
	Each	Vernier Gas Pressure Sensor	Existing Lab Equipment	$83.00	1	$83.00	$0.00
	Each	Vernier LabQuest	Existing Lab Equipment	$329.00	1	$329.00	$0.00
138830	Each	Workforce HangAlls Carabiner	Home Depot	$2.99	1	$2.99	$2.99
					Total		**$94.08**

Tether

Part #	Unit	Item	Supplier	Cost Per	Quantity	Item Cost	Our Cost
	Each	Electrical wire, 500'	Home Depot	$36.41	1	$36.41	$36.41
	Each	Nylon rope 50 ft	Home Depot	$6.58	1	$6.58	$6.58
	Each	Pool Noodle	Sullivan's Toy Store	$1.99	2	$3.98	$3.98
					Total		**$46.97**

Video Cameras

Part #	Unit	Item	Supplier	Cost Per	Quantity	Item Cost	Our Cost
91309	Each	Underwater Camera with Black and White Monitor	Harbor Freight	$129.99	2	$259.98	$259.98
					Total		**$259.98**

Prototyping

Estimated Cost	**$25.00**

Control System

Part #	Unit	Item	Supplier	Cost Per	Quantity	Item Cost	Our Cost
38391	Each	12 Volt Jump-Start and Power Supply	Harbor Freight	$49.99	1	$49.99	$49.99

10050818	Each	30.6 qt. Watertight Tote Clear	The Container Store	$14.99	1	$14.99	$14.99
W991444	Each	HiTechnic DC Motor Controller	Existing	$79.95	4	$319.80	$0.00
9841	Each	NXT Intelligent Brick	Existing	$149.99	1	$149.99	$0.00
					Total		**$64.98**
					Robot Total		**$713.32**

Estimated Trip Costs	
Accommodations	$500.00
Food and Misc Costs	$300.00
Total	**$800.00**

Donations	
Aurora	$250.00
Papa John's Pizza	$60.00
Central Childrens' Charities	$1,000
Total	**$1,310.00**

Total Funds Remaining	
Robot Total	$713.32
Estimated Trip Costs	$800.00
Donations	$1,310.00
Trip Subsidy	$203.32
Funds Remaining	**$0.00**

Note that Sidwell Friends School subsidized the trip, helping us break-even.

Appendix B – Division of Labor

Frame Design and Construction

Seth Drew
Ariana Eisenstein
Matthew Kim
Chitti Raju
Sam Stevens
Harry Webb
Albert Xie

Electrical and Control Systems

Isaac Dykemann
Colin Kelsall
Nora Kelsall
Rodrigo Lopez-Uricoechea
Jesse Pollak

Website Development

Raymond Jacobson
Justin Lau

Programming Team

Alejandro Alderman
Evan Brown
Rodrigo Lopez-Uricoechea
Jesse Pollak

Sponsorships

Ariana Eisenstein
Colin Kelsall
Rodrigo Lopez-Uricoechea
Chris Lu

Research and Development

Isaac Axtmann
James Atschul
Danny Baker
Maxim Baranov
Jack Borthwick
Alex Cox
Chris Dock
Neema Ghavimi
Jamal Maddox
Chris Meyerhoff
Guy WIlson
Paul Phelps
George Wojcik

Computer-Assisted Design Images

Harry Webb

Depth Meter and Water Collection Implementation

Colin Kelsall
Rodrigo Lopez-Uricoechea

Public Relations

Cecelia Auerswald
Gayatri Das Gupta
Meredith Stabbe

Manipulator Design and Construction

Chitti Raju
Harry Webb

Appendix C – Computer-Assisted Design Images