AUVSI Robosub

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Team 09

Final Report

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1) Introduction

1.1) Overview

The Association for Unmanned Vehicle Systems International (AUVSI) hosts an annual autonomous underwater vehicle competition. The NAU AUVSI Robosub team is a group of senior mechanical and electrical engineers who are tasked with entering and competing in the 2016 AUVSI competition. Participation in this competition is our capstone project. Team 9 has completed a second round of designing while building the “Trident” autonomous submarine, which will compete in the competition, next year.

1.2) Competition Constraints

There are several constraints that must be met when considering designs for the RoboSub. Due to the nature of the competition, they are all more-or-less equally important; if the constraints are not met, the team runs the risk of being disqualified and being unable to compete the task. First and foremost, the RoboSub must be autonomous. It may not be controlled by or communicate with an outside source, and must do all of its problem-solving and decision-making independently. It must weigh less than 57 kg, and fit into a box not exceeding 1.83 by 0.91 by 0.91 meters. Another consideration for the competition is that the robosub must complete all tasks within a designated time of fifteen minutes. It must have a clearly marked manual kill switch accessible from the outside designed to terminate power to all propulsion components. This is done to prevent injury or damage to the equipment or other participants in case of malfunction or error. The sub must be electrically/battery powered, and the batteries must be sealed to reduce risk of damage or corrosion; the batteries cannot be charged inside of sealed vessels, and open circuit voltage may not exceed 60 VDC. Except for torpedoes and markers, no part of the sub may detach during the runs. The sub must be able to be slung on a harness or sling for measuring, transportation, and safety purposes. Failure to meet one or more of these constraints, including additional ones not detailed here, can result in the team’s disqualification from the competition.

1.3) Competition Objectives

The competition lists numerous tasks that can be completed to gain points during the competition. The first task that must be completed is that the robosub must pass through a gate. Other tasks involve hitting targets with a torpedo, make contact with targets that are of a certain color while avoiding other colors, and dropping markers into a bin after removing the lid. The task map can be referenced in Appendix A. All of these tasks must be completed autonomously meaning that there must be a great deal of programming to make the sub recognize different shapes and colors.

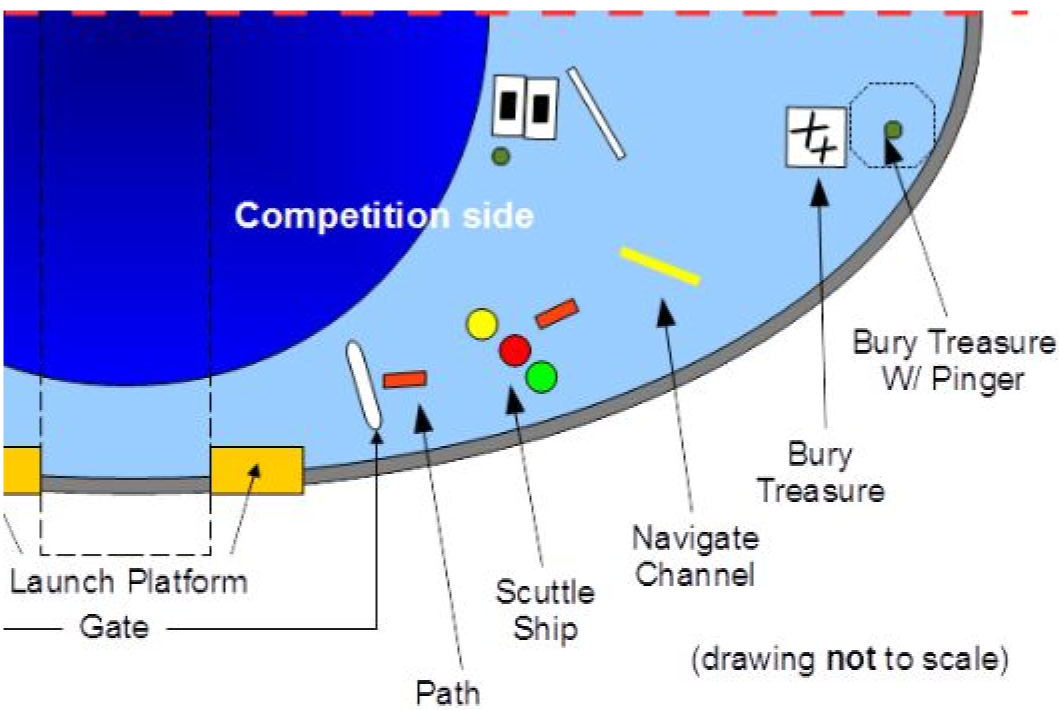

Figure 1: Competition layout

2.) Current Design

2.1) Introduction

This section describes the current implemented design of the robosub assembly. This follows months of prototyping and design changes after several testing sessions both in and out of the pool. These design choices reflect both lessons learned from these testing processes and decisions made with limited time and resources.

2.2) Thruster Layout

The thruster layout has remained mostly the same, with some layout changes necessitated by the reconstruction of the external brackets and hull throughout the various iterations of the submarine. As shown in Figure 9, the current thruster layout has 3 thrusters forward and three thrusters up. This is not ideal, and was only resorted to due to the metal frame being required for testing. The front and back thrusters are cantilevered, which introduces the possibility of vertical or lateral movement; the vertical movement would be exceptionally visible on the vertical thruster due to the attachment point being on a perpendicular axis, allowing the thruster to rotate the entire L-frame it is attached to. Ideally, the thrusters should be solidly fixed to the frame for the thruster pairs which are closer to the main bulk; this would be accomplished by "welding" the brackets that the thrusters are mounted to onto the submarine by using an ABS slurry (covered in the Operations Manual).

2.3) Hull Design and External Brackets

In order to put extra strength in the sub, the team came up with the L channel brackets to connect the sub tubes together as a whole system, as is shown in figure 3.3. The L brackets not only connected to the front and back thrusters, but also lock the side thruster. Also, the L brackets have multiple holes drilled in them so that the team can change the location of the thruster as needed. What's more, the L brackets can prevent torsion of the tubes when the thrusters engage with each other, so that the sub can stay stabilized.

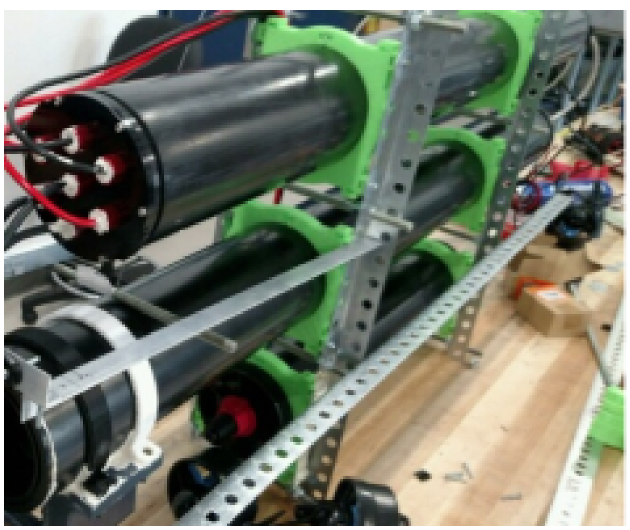

Figure 2:L-channel brackets design

2.4) Camera Box

Originally, the camera box design involved the use of a machined PVC block, with 2 acrylic windows bolted in place, fastened to the tube using two custom 3D printed clasps with a rubber gasket in between to ensure a water-tight seal. This design required a hole in the tube to insert the cameras into the box as well as a small camera mount that could fit through this hole and orient the cameras in the proper direction. Figure 3 shows an exploded view of the assembly. In manufacturing this design several problems were encountered.

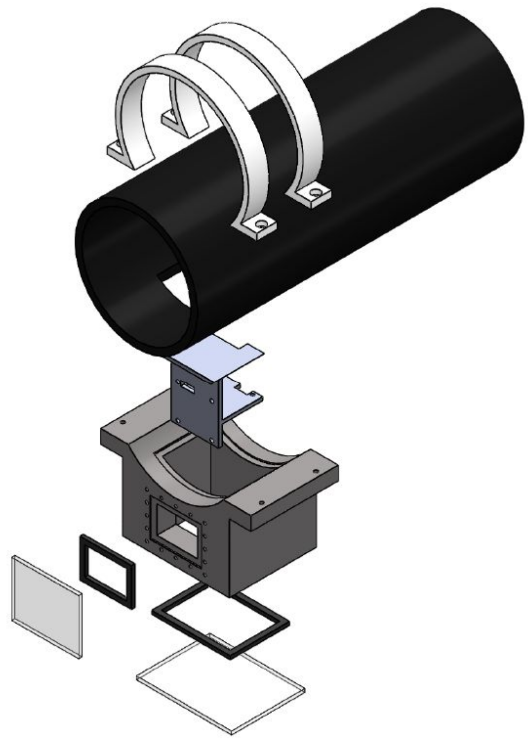

Figure 3: Exploded View of Camera Box

First, the holes that were supposed to hold the bolts for the windows in place would be too small to tap into the brittle PVC, thus requiring a different attachment. A special “acrylic cement” epoxy was chosen as it was determined to create the best seal possible without mechanical fasteners. Later, depth testing would validate this design decision.

Next, the tube that was purchased to house the control section was not perfectly round. This created a very serious problem as the round part of the box needed to fit uniformly against the surface of the tube to evenly distribute pressure on the seal. Any variance in the pressure distribution could allow water through the seal. The first depth test showed that this seal had been breached and action had to be taken to amend this failure.

The current camera box design is an amalgamation of the original design and several changes that had to be made after water testing failure. Epoxy was added to the entire edge around the camera box-tube connection as well as acetone plastic weld to the clamps to ensure that water could not leak under them. Figure 4 shows the design as it now. Depth testing on this design yielded very minor leakage that could be mitigated with some absorbent material, but a new camera box design will be needed for an absolutely water tight camera holder.

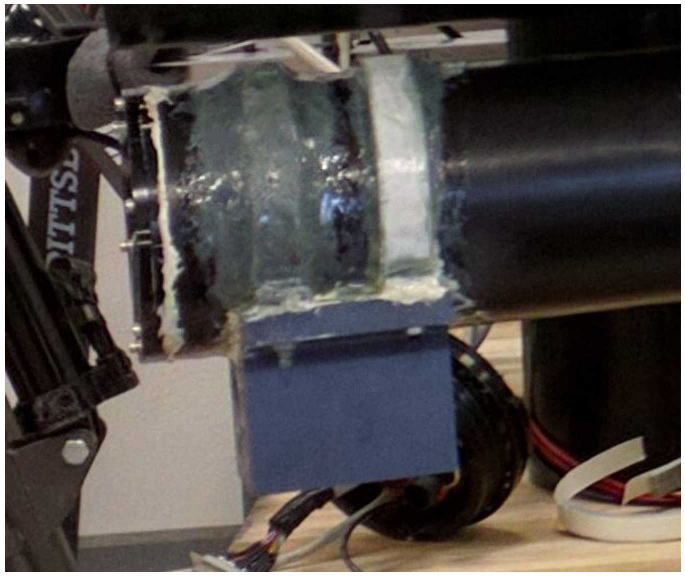

Figure 4: Camera Box with Acetone Plastic Weld

2.5) Ethernet and E-stop switch

For ease of testing, a removeable ethernet connection was needed between the control section and an external computer. This had to include a water tight enclosure that could house the ethernet connection and be removed for competition. To this end, a simple pipe design implemented. This involved a 1 inch pipe to house the large female-female connector while using half inch to one inch adaptors with hollowed epoxied bolts, similar to the endcap through ports, to seal the cables. Since the bolts use conical pipe threading, their connection to the adaptors, and thus the pipe, is water tight. This allows for the bolts to be removed as needed.

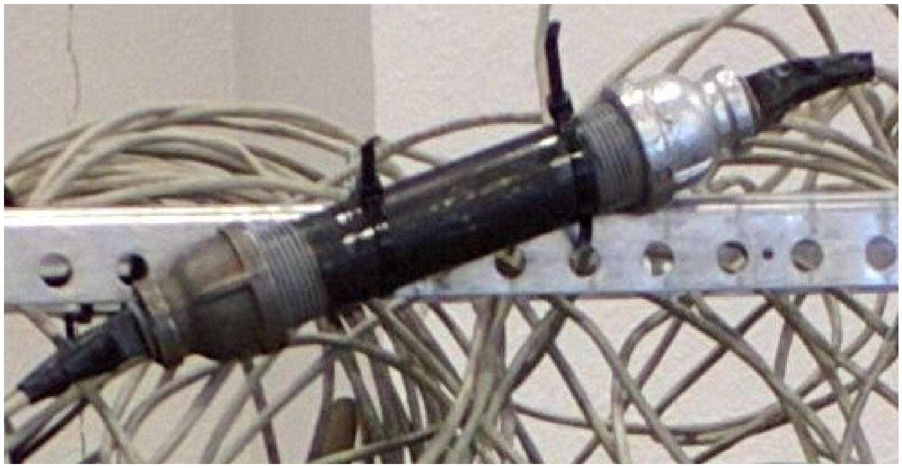

Figure 5: Ethernet Connection

2.6) End caps

End caps are needed to keep the system watertight while still allowing the electronics system to be removeable. The end caps used are shown in the assembly drawing below. The double radial o-ring seal shown uses rubber gaskets that fit onto an aluminum flange and provides a watertight seal within the inside of the tubes as well as an o-ring between the connection of the end cap to the aluminum flange to keep the end cap connection watertight. To keep the cable through-ports watertight, rubber o-rings were also used between the head of the bolts shown in figure 7 and the endplate.

Figure 7: Bolts for Through-Ports

Figure 6: Exploded View of Endplate Connection

The team decided to use aluminium endplates, as opposed to acrylic, because they are easier to machine and allow heat to escape the system more readily.. The batteries are the warmest electronic components in the system and they were placed closest to one of the end caps so that the heat will dissipate to the end cap and be cooled by the water outside of the system. The end caps were machined with through holes to fit the necessary amount of bolts, and the bolt through holes were machined to the closest size for each individual cable to ensure a tight fit.

The final image of two of the resulting plates is shown below. It can be seen that the cables were epoxied into the bolts to add an extra watertight barrier. By using connector pieces to connect these cables to the internal cables, the bolts are removable from the endplates if needed.

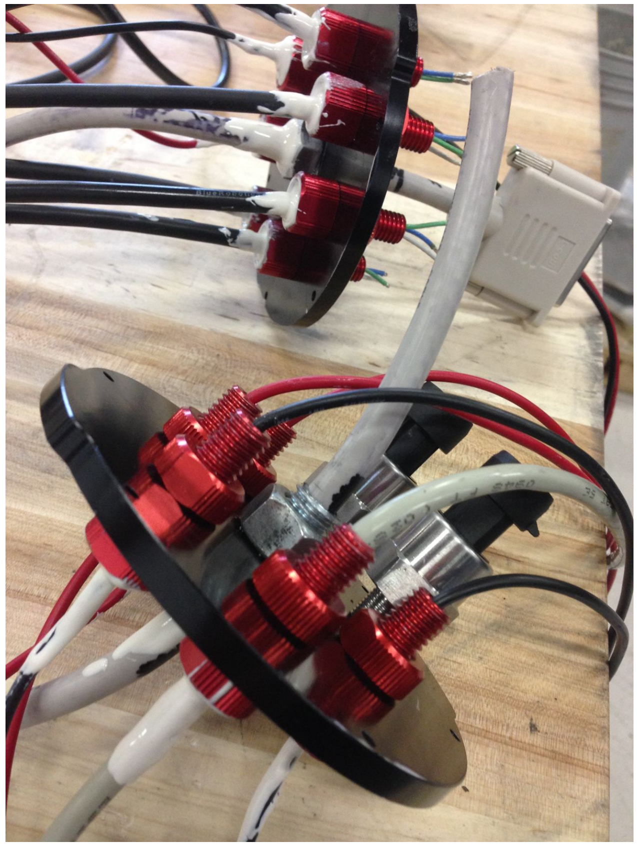

Figure 8: End Cap Final Assembly

2.7) Internal Frame

The new design of sub has two tubes because there is a lot of hardware. The first tube is the high power tube, this tube will be oriented on the top. The other tube will be in the bottom. It will contain the sensitive electronics.

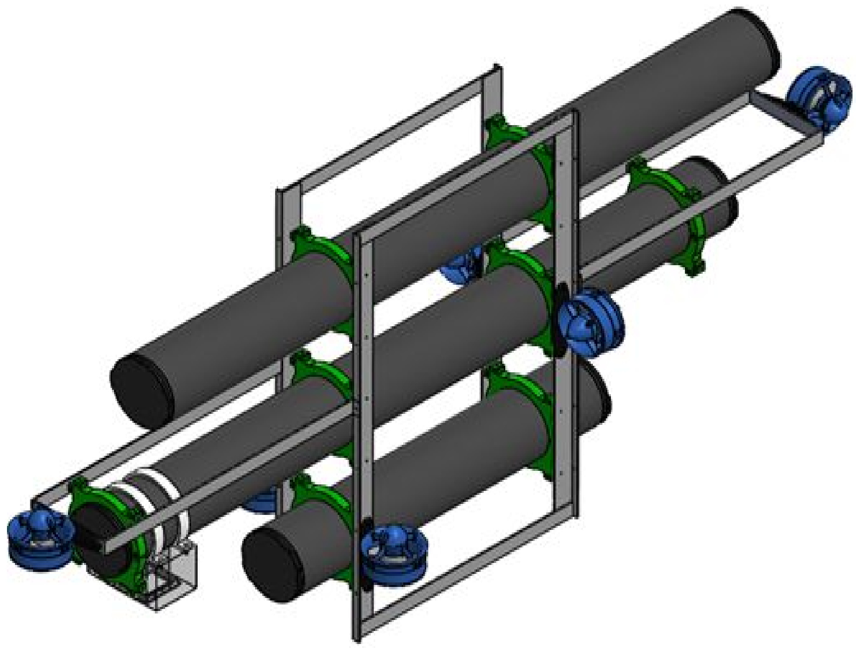

Figure 9:Current mechanical Trident assembly

Using multiple sections for different parts will make it easier to change if any part has a problem. The sections in the high power tube are main motor batteries, terminals, board holders, buck and electric speed controllers, ESCs, and DB 25 connector holders. For the sensitive electronics tube on the bottom, we put a Raspberry Pi (RPI) and boards towards the front, board holder Hubs in the middle, and DB25 connector in the back. There is also an empty space to put a sonar and small batteries, if needed in the future. The team made a water detection system to detect any water leaking to avoid any damages to the sub or lithium battery. The sub will have four water detectors; each tube will have two of them, one in the front and one in the back. There is a section called the "4-2 connecter"; This section would be the last part in each tube. The 4-2 was made for two main reasons - to protect the main cable of the sub which the db25, and to have a good orientation of the sections inside the sub.

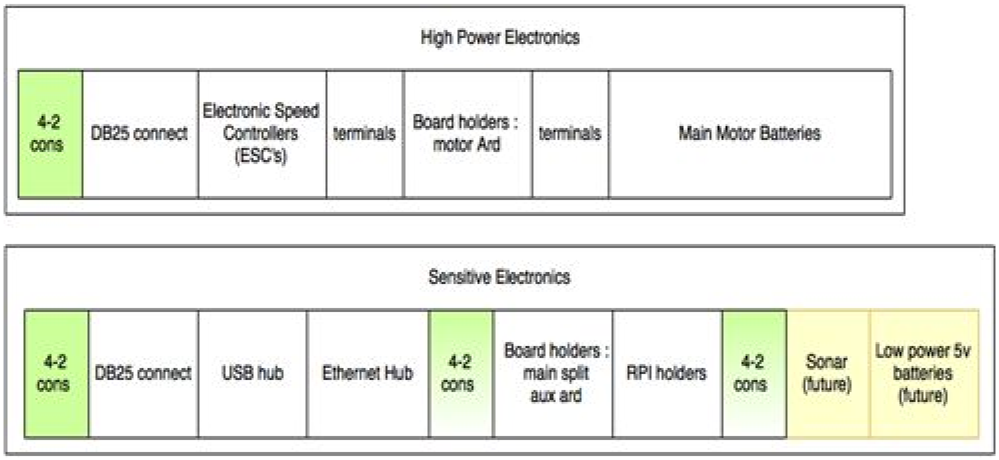

Figure 10: Internal layout

The electronic speed controllers (ESC's) will generate a lot of heat inside the sub. This heat might affect a lot of the sub's parts such as the wires and the lithium batteries.Because of this, heat sinks were added to absorb some of the heat, but it was not enough because the sub is closed and the plastic tube is a fairly strong insulator. The above described aluminium end caps help to dissipate some of this excess heat. For the short duration testing the team has done, this is enough, though further heat negation is advised for the sub to handle the 15 minutes or more it will be operating at competition.

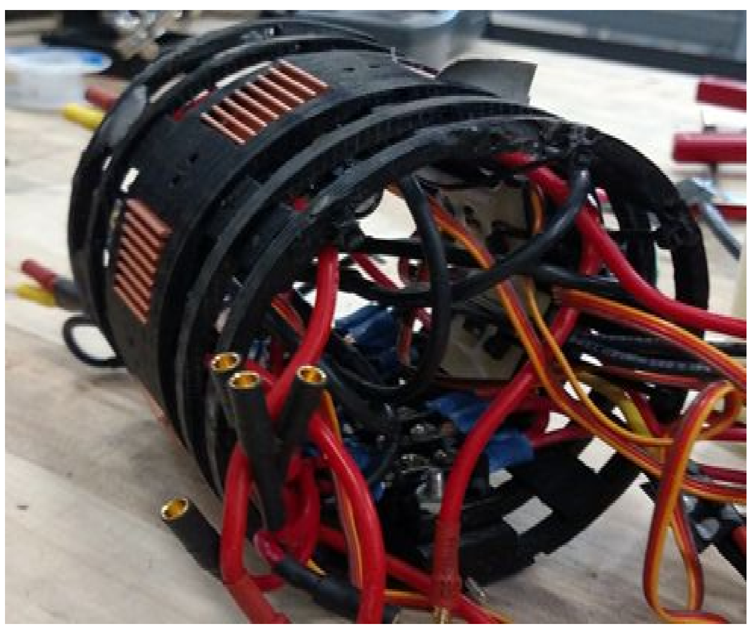

Figure 11: ESC holder

Since the sections are very complicated to manufacture, we have to use 3D printers to manufacture them. Each section has a big enough gap to avoid overheating and any electrical faults. Each section has two holes on the top and in the bottom, in order to attach all the sections to install them in the sub. The average of thickness for each part is one inch to give enough room for the wires.

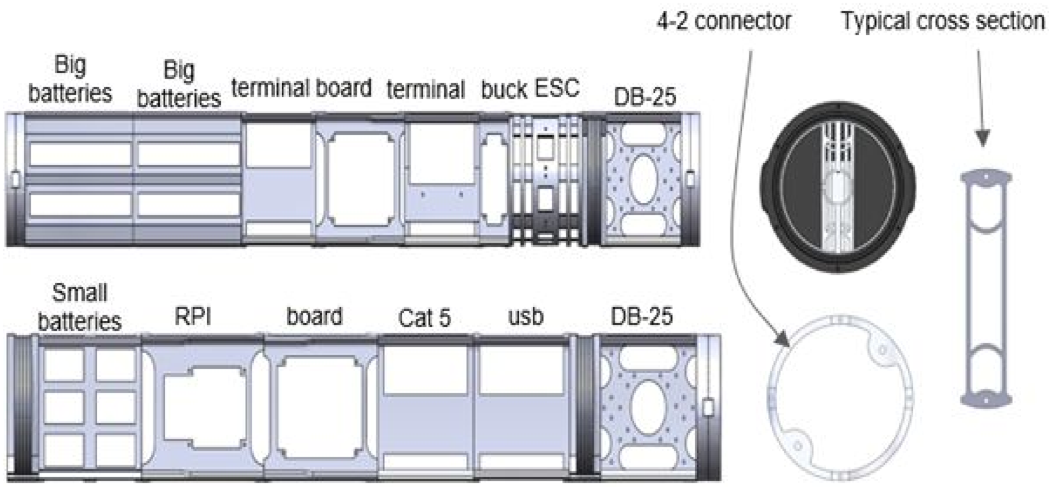

Figure 12: Internal CAD

The team took advantage of all the printed parts that were not used because of failed prints or redundancies to hold wires and protect them inside the sub. While installing these sections inside the submarine, the team faced a problem - the tubes were not perfectly circular, which meant that the sections needed to be sanded to fix that problem.

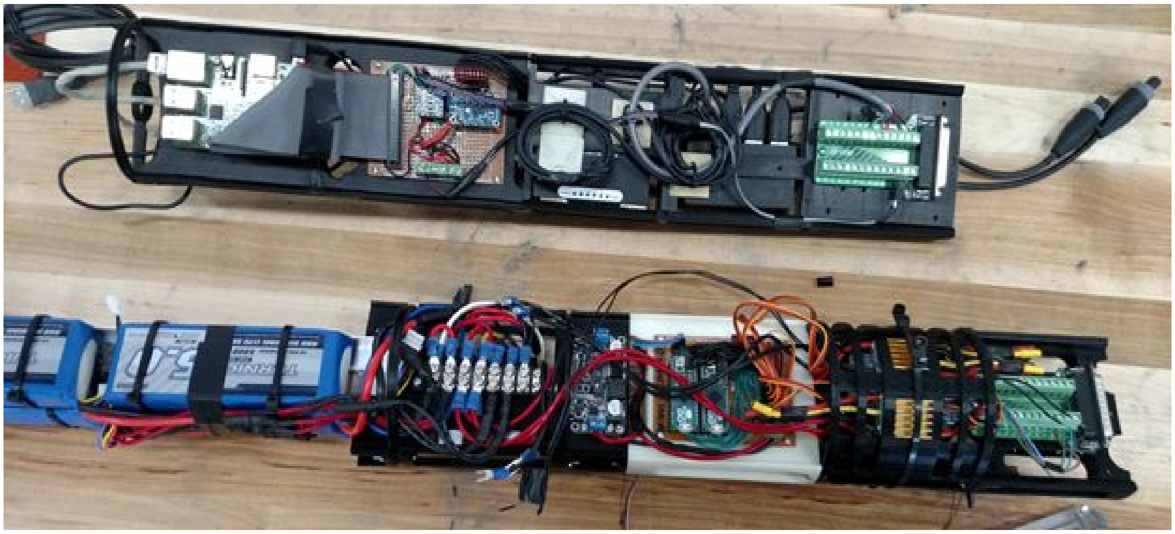

Figure 13: Internals

2.8) Hardware

Control Section

The control section is complete enough to have ROV (Remote Observation Vehicle) abilities however, the autonomy could not be achieved due to software hold backs which will be detailed in the next section and later sections.

The control section comprises of 2 RPI's, a USB hub, an ethernet switch, 2 5v batteries, a non-complete auxiliary arduino board, a splitter board with IMU, and a Data Bus (DB) 25 terminal breakout.

Power Section

The power section connects to the control section through the DB25 terminal breakout. The section is comprised of of all the Electronic Speed Controls (ESC's), the motor control Arduinos, the main batteries, the E-stop relay system, the buck converters, the terminals, and the DB 25 terminal breakout. Please reference the detailed schematic in the appendix for more details.

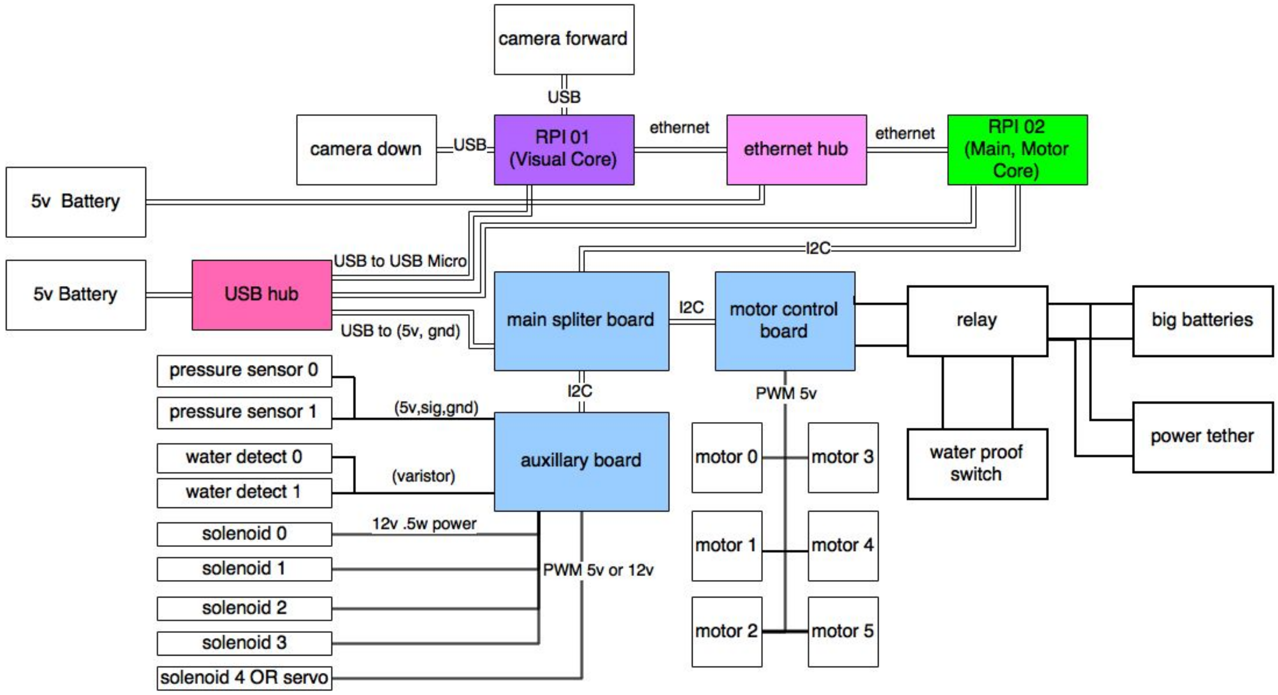

Figure 14: Hardware diagram

Power Tether

During long testing periods, the power of the batteries will not last long enough for a full testing time. So the introduction of an external power tether was necessary. This allows for longer testing times at the expense of having non-competition strain from the cable on the sub.

2.9) Software

Main RPI

The current software design consists of many object oriented modules split amongst two raspberry pis. There is one main program on one of the raspberry pis that calls other programs and coordinates inputs and outputs to these various programs. For example, this main program will receive analog input pressure readings through I2C and the main program sends output to the motor class based on these readings. Although parts of this action have been completed individually this type of complete action was never actually implemented during testing in the pool, but most of the code is written to create it.

Visual RPI

The other raspberry is solely used for image processing. There is one main image processing class which calls several other classes. These include a class for line processing, a class for circle detection and a very rudimentary start at image detection for the PVC U-shaped task. The line detection module is pretty well developed and provides good output although it was never tested in the pool. The circle detection picks up circles well, though the output needs to be turned into something the motors can use, like in the line detection algorithm. The PVC U-shaped detection still needs more development.

Currently, in the sub's ROV status, motor commands are able to be sent to the main program through an ethernet tether to control the sub in the pool. The below schematic is a smaller and simpler way that the sub could have operated, however this schematic was never fully implemented.

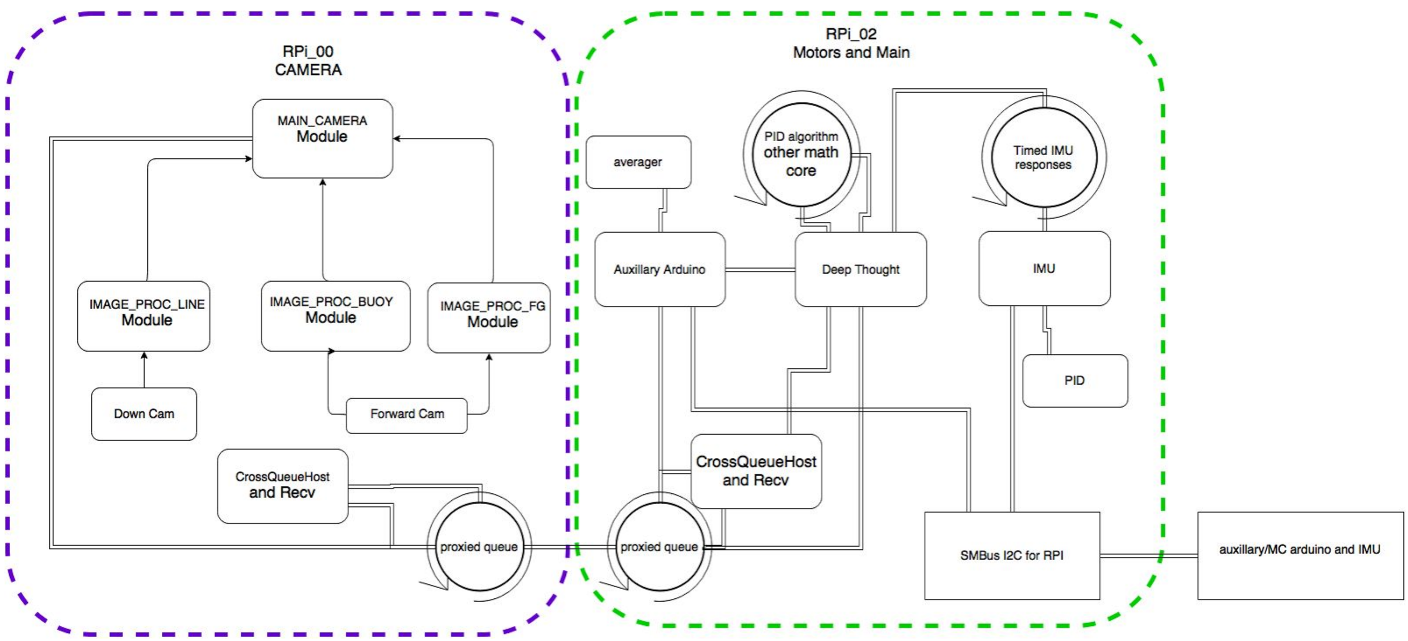

Figure 15:Software diagram

3.) Future Design Additions

3.1) Introduction

After pool testing the sub multiple times, the team came up with several new designs that would increase the effectiveness of the sub. Sadly, due to time and budget constraints, the team is not able to implement these designs. What follows is all of the future additions the team would like to implement but will not be able to. This section will stand as recommendations to future NAU robosub teams.

3.2) Thruster Layout change

With the current, metal-framed design, the thruster orientation causes undesirable rotation of the submarine during powered motion. The location of the thrusters needs to be fine-tuned through calculation of the center of buoyancy (CoB) of the submarine to ensure the movement is fluid and the submarine does not veer in any one direction or rotate during diving/surfacing procedures. To ensure the locations are final and the CoB does not need to be recalculated, it would be prudent to replace the metal frame with the initial desired "modular" system (the U- and X- brackets) and fix them in place after determining where the thrusters need to be placed. In addition, this would make the Trident more maneuverable due to the programmers and programs not having to "fight" against asymmetric placement.

3.3) Hull and External Brackets change

The team has decided to go back to the old U/X design due to simplicity and ease of repositioning/adding components. However, due to the need for additional ballast, it has been decided that the lower halves of the bracket sets should be made out of machined metal; the dimensions of the mounting holes would be the same, but the design must be simplified to allow ease of manufacturing.

In addition, metal plates will be mounted on the sides. This is to provide additional ballast and prevent torsion of the submarine assembly as a whole. Also, it would allow a space for the logos and emblems of sponsors to be displayed on the sides of the submarine, or space for additional instrumentation that may be required in the future to be mounted.

3.4) Camera Box and Light Change

Figure 15 shows the light fixture that was purchased for the sub. This light is not yet water tight so future teams will need to find a way to make it so. This team's idea was to seal all the edges with silicone or epoxy, however the heat produced by the light will need to be accounted for.

Figure 15: Lights for Submarine

After several attempts to salvage the current camera box, the team has decided that a new camera box design is necessary. The new design idea is to use 2 different external camera boxes. This will ensure that any leaks in the camera boxes will not compromise the entire control section as the current design may. Figure 16 shows the dome piece that was purchased to facilitate the creation of these new camera boxes.

Figure 16: Blue Robotics Acrylic Dome

3.4)Torpedoes

The planned torpedoes for the submarine would use a compressed air tank to create a force strong enough to launch them into the target. Such a pneumatic system could also be used for other systems of the sub such as the clasp and marker dropper. The main idea is to add 3 ball plungers screwed inside of the torpedo tubes, as is shown in Fig.3.5. The purpose of these plungers is to lock the torpedo inside of the tube, so when the sub is underwater, the pressure of the water won't move the torpedo. The back torpedo connector would be permanently attached to the frame and have a ¼ inch standard pipe thread to attach the tube from the pressurized tank to a pneumatic solenoid. To fire a torpedo, the pneumatic solenoid will actuate to release compressed air unlocking the ball plungers and shooting the torpedo out.To aim the system, a lazer could be placed such that the foreward camera would be able to see it and pinpoint the torpedoe's trajectory.

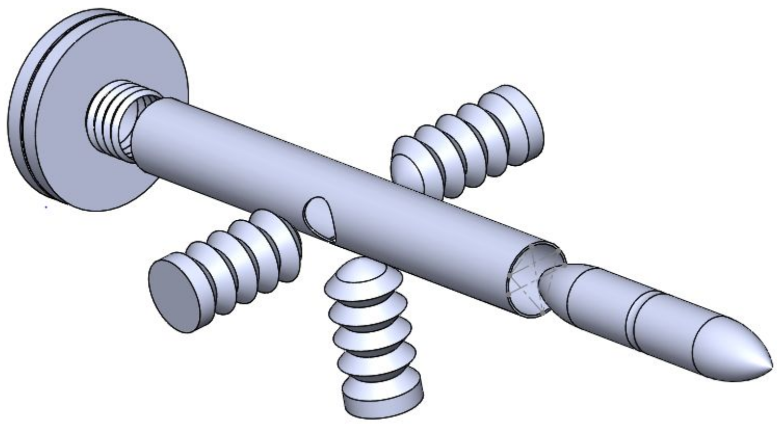

Figure 17: Torpedo Design

3.5) Clasping

The clasp system is currently in the design stage, and needs only minor modifications to begin manufacturing. The idea behind it is that the claws have teeth around the pivot point, and a sliding rack opens and closes them. The rack will be actuated by either a waterproof servo motor or a pneumatic actuator; currently, it is designed for the servomotor. The length of the grasping "claws" may need to be extended based on the size of objects that are planned to be grabbed; in addition, the thin slabs which fix the claws and slider together should be printed of around 50% infilled ABS plastic, milled from a *non-brittle* plastic, or milled from a lightweight metal. The baseplate is designed such that it can be attached to the modular brackets so the clasp points vertically down, but should be easily modifiable to allow other angles or other methods of attachment.

3.6) Electrical

Splitting the Auxiliary Board

There's been a software issue that could be more easily managed with some hardware changes to the auxiliary board. The idea is to make 2 new boards completely: one for reading the analog reads of the pressure and water detecting. The other will use the GPIO ability of the RPI to accomplish controlling the H-Bridges that will control solenoids and other high power on off applications. However, the another Arduino would have to be introduced if other needed PWM abilities, other than the motor control, are to be implemented.

Also depending on the wattage of the the lights that will be implemented on the submarine, there may have to be the introduction of higher power created MOSFETs to power these electronics. An easier route may be to use the phidgets that were donated to NAU by a high school down in the valley. They could be rigged to work as high power DC controlling devices for whatever reason.

Sonar

The introduction of a Sonar or hydrophone board will require the dedicated work of an entire EE team. This means the full design, simulation, testing, debugging, and integration into the rest of the submarine. This is a big enough task to be an entire capstone in itself. The team should buy or build some sort of ultrasonic pinger source in order to test the ability of the board to tell the sub where to go. The members of the team should also be well versed in DSP concepts and have a good grade from EE348 or EE448.

The board should be a surface mount design with minimal extra wiring and minimum amount of layers as to reduce any unwanted capacitive effects. Also most hydrophones, including the ones that were specified out in the BOM, require a high input impedance for it to work. Also, at the higher frequencies the hydrophones behave un-ideally, meaning that there will have to be tests to ensure that the hydrophones operate well enough to perform the readings. This all has to work with the rest of the control system of the submarine. This means that the frequencies that the 5v batteries put out with their internal buck converters, will have to be dealt with. This could be done with some sort of capacitive array that charges them while doing the measurements of the hydrophones. Hopefully the hydrophone board could be optically isolated from the big power sections which should get rid of the noise from the ESC's.

Another reason the team will have to use some sort of simulation software is because there might be saturation issues with the board, meaning there have to be dynamic gains. This is due to the vast change in distances from one part of the competition to another part of the pool. However, as the hydrophones get closer to the pingers, they may become saturated from the fixed gain. There is a way to introduce an analog multiplexer which, when used with different feedback resistors for the many operations amplifiers, can yield gains that then can be inputted into ADC chips. The ADC chips need a fast enough sampling rate in order to not alias the signals coming in. This also means that there needs to be an analog High pass filter that get rid of higher frequency noises that might alias down to the range that the hydrophones are at. Please reference the diagram in the appendix for more on a preliminary design of the sonar.

There can be noise issues that would have to be seen and avoided. These noises may come from the environment, from extra noise from the other team's propellers, or it could come from the other pingers because there could be up to 8 pingers in the water which could throw off hydrophone array. These noise issues would be solved with DSP processes.

The entire Sonar system would have to be communicationally connected to the rest of the sub in some sort of fashion. This may be through the same I2C interface that is implemented elsewhere or by using some other interface or a custom one. Tribulation software may also have to be implemented if needed, depending if the sub would work with a point and look algorithm, or if a full capture then triangulate algorithm. The first one is easier to implement however, it would require more time in competition. The direct triangulation would mean that once a snapshot has been taken, the data that is sent back would be enough to plot the entire course correction to navigate to the pinger.

Some idea on how to have the RPI interface to the board, would be through a direct GPIO cable which, when that particular RPI has done all the DSP processes on the data, would then send the data to the main core through the ethernet.

Introduction of another Raspberry Pi

The introduction of another RPI for computing large data sets might be good for 2 reasons: large sets of fuzzy logic input, and for the triangulation with the sonar section. This would ease computation time, allow the main core to not be bogged down, and have a good feed back with the IMU. Plus, depending on the algorithm for the sonar, the computation might be so intensive that there would be no better way. The DSP algorithms are computationally intensive so keep that in mind.

Water detectors

There was a design for a water detector that didn't end up viably working. There were too many wires to route that would have been obstructed by the water detectors. Some teams had used humidity detectors and would fill the hull of the sub with inert gas of some sort. If there was a leak, there would then be a few minute water particles however, this would take some research and engineering to figure out a good solution.

3.7)Future Software

I2C detect motor glitch

There is a small fixable glitch within the I2C detect. When running the terminal command "i2cdetect -y 1" with the ESC's powered on, there's a glitch. The i2cdetect sends the bytes [0,0,0] which will register on the arduino MC's as turn on motor 0 to 0 power. However, the 0 power means the most negative power setting. So when doing the detect command. The sub's 0 and 3 motor will turn on in full negative. This can be remedied with an if statement in the i2c command receive function in the arduino MC code.

Manual control queue location swap

There are 2 main classes that determine a way to communicate between cores or entire RPI's on the sub. The manual control of the sub is holding the queue on the MAC that is connected to the sub. However, for full autonomous control, the queue needs to be hosted by the main RPI. This means that the MAC manual sub control will have to try and access the queue and there will be a delay start to the display window that allows for the keystroke event detector that determines the manual control over the sub.

Full IMU revamp

There was a mess of software to try and use the IMU which maybe should be done from scratch. There was some ideas in the class of IMU that might be helpful, however there are only a few methods that should be used from the IMU class.

Visual dynamic thresholds

Implement a better search algorithm for the initial threshold parameter in the line circle detection algorithm. A linear search is currently being used. This is slowest part of the visual detection algorithm, since for each threshold parameter that is checked this triggers an entire chain of function calls that may or may not capture lines on the image. There are other implementations for image detection that could involve drastically changing the algorithm.

Lighting

Another option that might eliminate the need or decrease the range of parameters to search through would be adding lights and creating a pulse width modulation option on these lights. The lights could pulse brighter until a line is seen. The difficult part of this would be adding the communication between the raspberry pi and the arduino where the lights are being pulsed.

I2C collision avoidance

There is a way to have a thread lock be passed to many different working cores and programs. This thread lock would only allow certain processes access to the I2C line one at a time. However, if there is a delay in the response of the I2C line for whatever reason, there's no way to time-out the request once the lock has been acquired.

It's quite the mess and there has to be some way around it. We think it's because of the current sluggish arduino software which is trying to do too much in too little time therefore doing an OS level delay on the SMBus library implementation that might create such a delay that the process of accessing the line at a low level messes up. So, making a quicker arduino and de-spaghettifying the python side code would be necessary.

System Safe Startup and Shutdown

The python programs on each RPI can startup automatically. To do so, a change in one of the OS files is needed, however there's an entire instructables on it. Doing this may pose a problem.

Increase Robustness

There is a massive amount of software on the submarine and no matter how much testing we have done there will always be some issues. This is where the ample use of try and catch statements in the software will create more robust working submarine. The use of try isn't enough though, as there has to be contingent software. This means if there's an accidental disconnect of wires or, if there's been a glitch, there will be a safe course of action.

Data Dump Deep Thought into a USB

We have created a class that will automatically mount and unmount. It will need to be implemented during testing and competition to document data including IMU snapshots and other important checkpoints.

Motor Input Priority

In implementing a fully autonomous robosub, future groups must answer this question: which inputs should have priority to give output to the motors? For example, if the camera and the IMU are both giving commands to twist on the Z axis, which should go first? Should one be ignored in certain cases?

4.) Conclusion

More than anything else, this project has been a learning experience. The differences between the initial sub design and the current sub are innumerable. Each subsystem of the sub, from the electronics to the brackets, has undergone several design changes as difficulties were encountered. Each of the first three pool tests necessitated huge changes and the sub evolved quickly over those few weeks.

The sub the team has now works. It is water-tight, has a durable frame, and is able to exert some thruster control. The electronics have been tested and are operational and the code that exists is solid. However, there are still many functions that sub does not have.

For the future, the team has several designs that we were not able to implement. These designs are described above, but, as our design process has shown, these will need to be tested and updated as they are implemented. The hope is that next year's robosub team will be able to put a fully hashed out design in the competition to complete all the tasks effectively.

APPENDIX

Appendix A

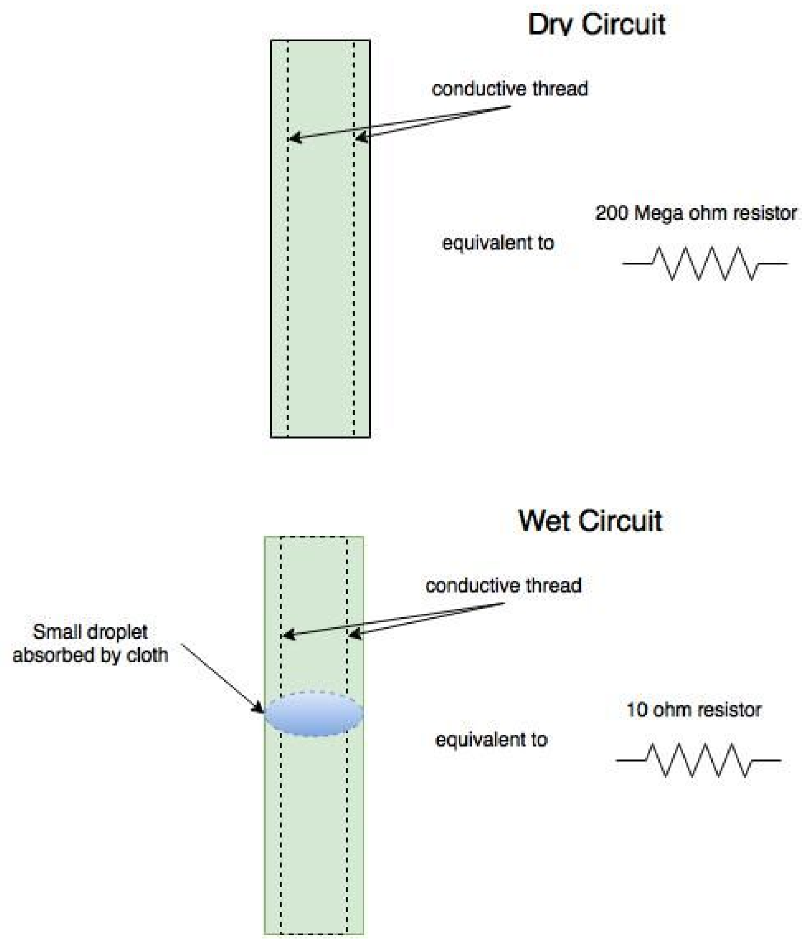

Figure A.1 : How the water detectors work

Appendix B (Bill Of Materials)

Table B.1 : Electrical Cost

Electrical Control	price	quantity	total Cost
Raspberry Pi 2	$38.76	2	$77.52
arduino micro	$24.99	3	$74.97
10/100 5-Port Switch	$40.01	1	$40.01

mini ethernet switch			
raspberry Pi 2 GPIO ribbon	$4.95	1	$4.95
micro USB cable	$3.86	3	$11.58
mini USB cable	$2.99	1	$2.99
USB powered hub	$10.95	1	$10.95
5Mp web camera(linux comp.)	$52.00	1	$52.00
2Mp 80degree view camera	$45.00	1	$45.00
2.54mm pins male	$1.80	1	$1.80
2.54mm socket female	$2.08	1	$2.08
PCB perf boards	$3.50	3	$10.50
4 channel voltage level shifter	$8.22	1	$8.22
Eyourlife Universal 30PSI Pressure Transducer	$20.99	2	$41.98
general op-amp	$0.00	1	$0.00
adafruit IMU	$27.89	1	$27.89
ethernet cable various lengths	$0.00	1	$0.00
terminals, PCB mounted	$8.19	1	$8.19
CS2N25MF-2.5	$21.55	1	$21.55
DB25-F connector	$7.99	2	$15.98
2-56 screws 1"	$2.53	1	$2.53
2-56 square nuts	$12.73	1	$12.73
terminal board DB25-M	$18.99	1	$18.99
total	x	x	$492.41

Table B.2 : Passive Sonar

Passive Sonar Assembly	*price*	*quantity*	*total Cost*
arduino duo	*$39.99*	*1*	*$39.99*
total	*x*	*x*	*$39.99*

Table B.3 : Motors and Batteries

Motors and batteries	price	quantity	total Cost
11.1V (3S) LiPo Batteries	$29.91	4	$119.64
5v battery	$14.99	2	$29.98
water proof killswitch	$10.00	1	$10.00
100 amp relay	$10.29	1	$10.29
screw connectors	$4.00	1	$4.00
eurostyle terminal	$3.87	1	$3.87
battery charger	$20.00	1	$20.00
barrel connector to xt60 connectors	$5.99	1	$5.99
buck converter step down	$6.78	2	$13.56
DC power barrel connector(phidgets)	$4.90	1	$4.90
12V fans	$7.99	2	$15.98
16AWG, 10A, 12Vdc rated wire	$22.95	1	$22.95
12v water pumps	$14.95	3	$44.85
BlueRobotics T100 motors	$109.00	6	$654.00
ESC 10A 3p rated 6-17V	$25.00	6	$150.00
3.5mm m&fm wire bullets	$3.87	3	$11.61
10 gauge power wire	$17.95	4	$71.80
total	x	x	$1,193.42

Table B.4 : Frame and Other Mechanical

Frame and other Mechanical	price	quantity	total Cost
			$0.00
3D filament	$21.98	3	$65.94
3D filament	$21.98	3	$65.94
4in ID Tube	$7.00	1	$7.00
Silicone Sealant	$5.00	2	$10.00
Fasteners	$25.00	1	$25.00
Super Glue	$1.50	2	$3.00

*PVC test structures *estimate**	*$150.00*	*1*	*$150.00*
total	*x*	*x*	*$326.88*

Table B.5 : Camera Box and Seals

camera box and others	price	quantity	total Cost
Weld-on glue	$8.00	1	$8.00
PVC block	$36.21	1	$36.21
WTE4-ASM-R1	$29.00	4	$116.00
Aluminum End Cap (4" Series)	$22.00	4	$88.00
Weld-on #40	$42.99	1	$42.99
total	x	x	$291.20

Table B.6 : Misc

Misc	price	quantity	total Cost
ABS tubes	$50.00	2	$100.00
Bullet Connectors	$20.00	1	$20.00
Light	$20.00	2	$40.00
Pipe fittings	$8.00	1	$8.00
total	x	x	$168.00

Appendix C (Circuit Diagrams)

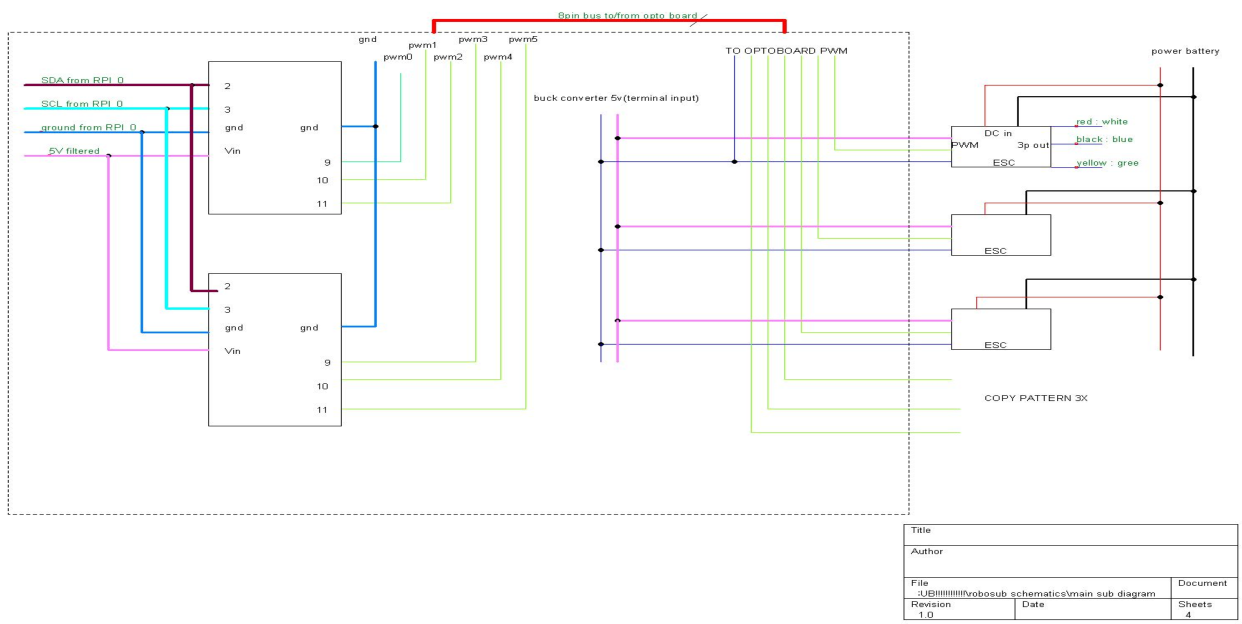

Figure C.1 : Power Circuit with arduino MCs

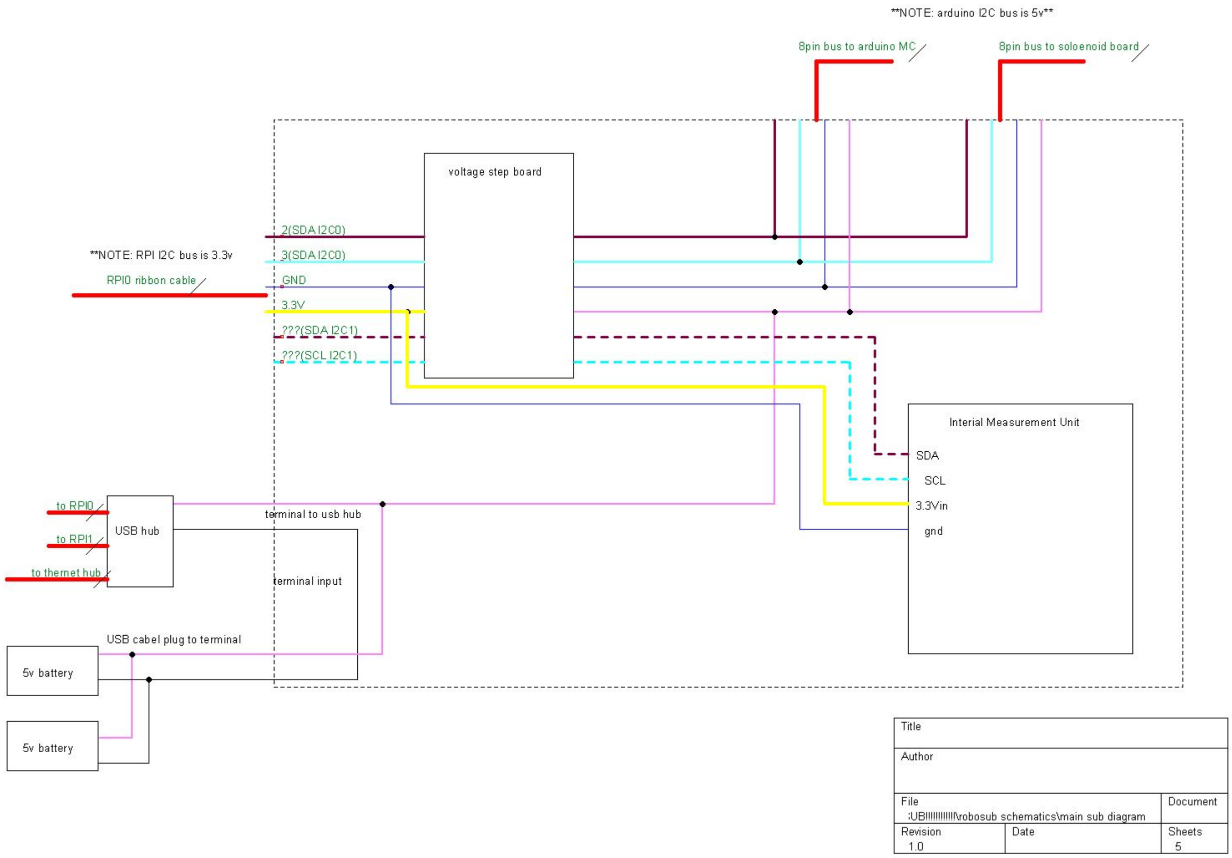

Figure C.2 : Split board

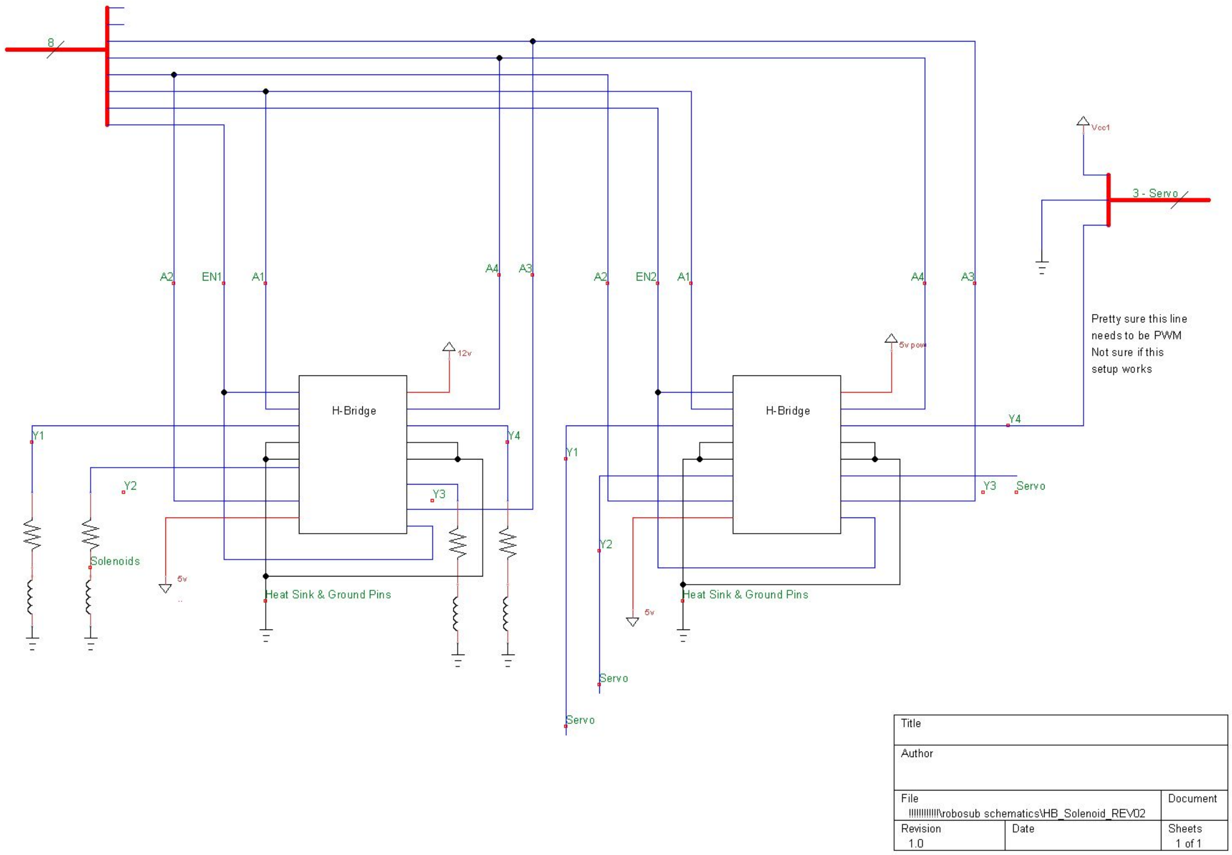

Figure C.3 Solenoid,lighting, and servo powering circuit

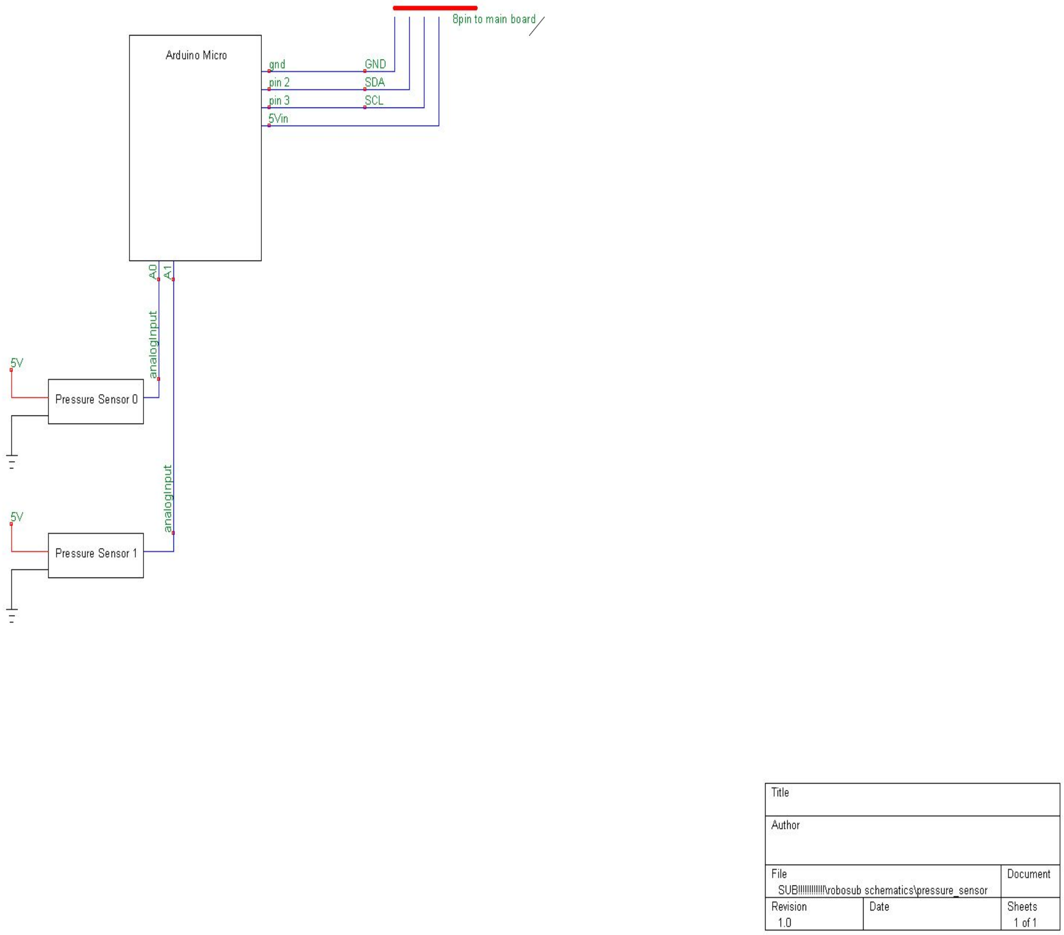

Figure C.4 Pressure, and water detecting circuit