Bubbles Under The Sea

The Greatest Underwater Submarine to Exist

Introductions

Group 19

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OUTLINE

1. Introduction and Motivation
2. Project Goals/Objectives, Specifications/Requirements
3. Overall Design
   a. Problem Approach (sub-outline)
   b. Block Diagram
4. Hull (Pressure and Aesthetics)
5. Ballast
6. Electrical Networking (Motors, Light, PCB)
7. On-board Pi interface and Camera and Sonar Sensor
8. Umbilical and Controller and land battery
9. Project Budget and Financing to date and end of project
10. Progress chart (with percentages)

Motivation

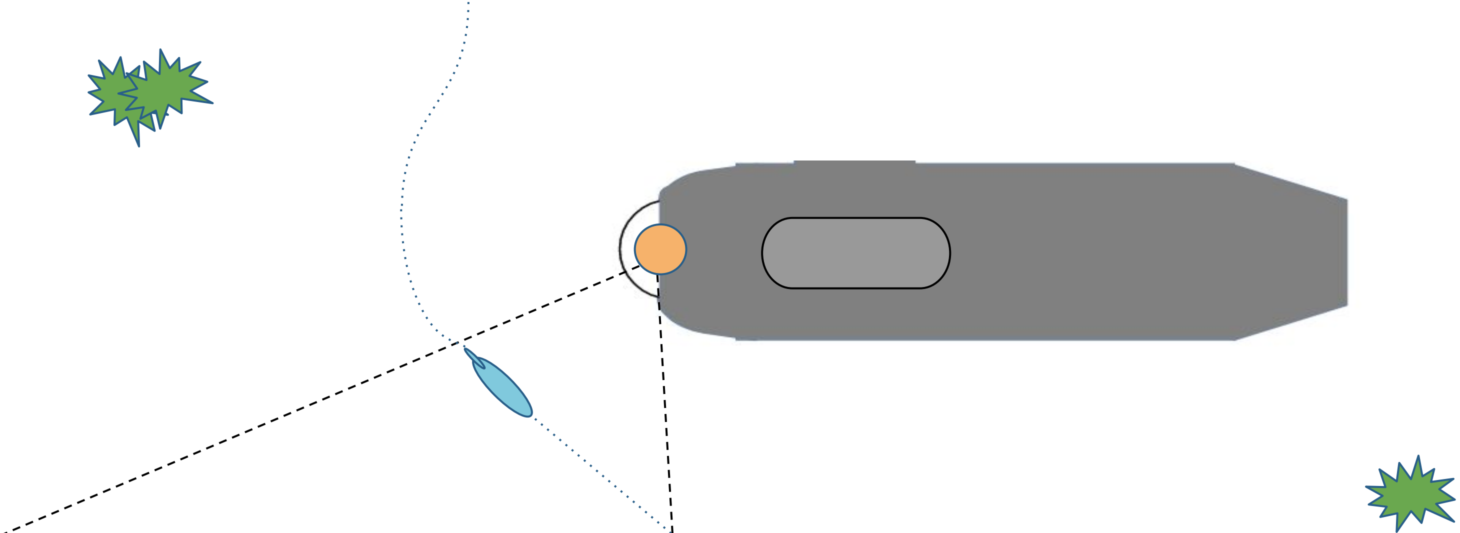
- Remote controllable submarines are used for exploration and visual inspection purposes.
- One of the main motivations of the project was to be able to put the underwater landscape in the hands of the disabled. A vast amount of people do not have the ability to see what it's like underwater due to various circumstances and with our Project we would be able to supply an affordable way to give them that ability.
- Most that are on the market cost well over $1000!
- Those below that amount have fixed view cameras, and static lights.
- We aim to improve the exploratory experience!

Submarine Objectives

- The ability to follow interesting objects or creatures underwater without the need to turn the whole submarine
- The ability for the submarine to livestream footage and sensor data
- The ability for the submarine to dive to at least 4 meters
- To make the submarine aesthetically pleasing

Potential Use Cases

- If an interesting creature passes the submarine at an oblique angle, the camera can be turned to follow it, as opposed to turning the whole submarine.
- If something interesting is to the sides, top, or bottom of the submarine, some areas can be seen using the rotating camera as opposed to none.
- Adjustable headlights provide more options to how people view dark underwater areas. With the lights adjustable, sensitive fish won't be frightened by bright lights, and image bloom can be minimized.

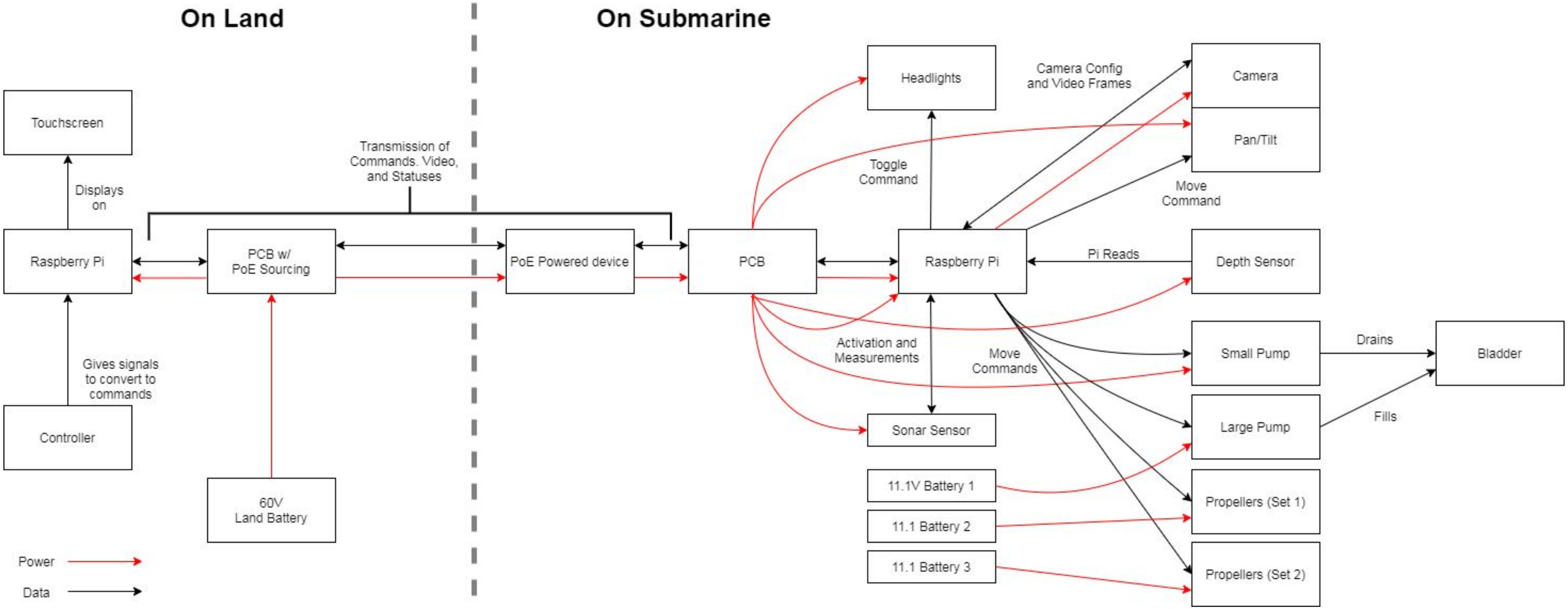


Specifications

Component(s)	Parameter	Specification
Pan/Tilt Mechanism	Controllable Angle	Can use the controller to pan and tilt the camera in a 75° half cone.
Controller and Controllables	Action Delay	< 100 ms
Camera, Pis, Display	Image Delay	< 100 ms
Battery	Discharge Time	1 hour
Display	Framerate	30 frames per second
Propeller Motors	Speed	0.15 m/s
Headlight	Adjustable Brightness	0 - 8000 millicandela
Hull	Temperature Resistance	4 - 33° C*

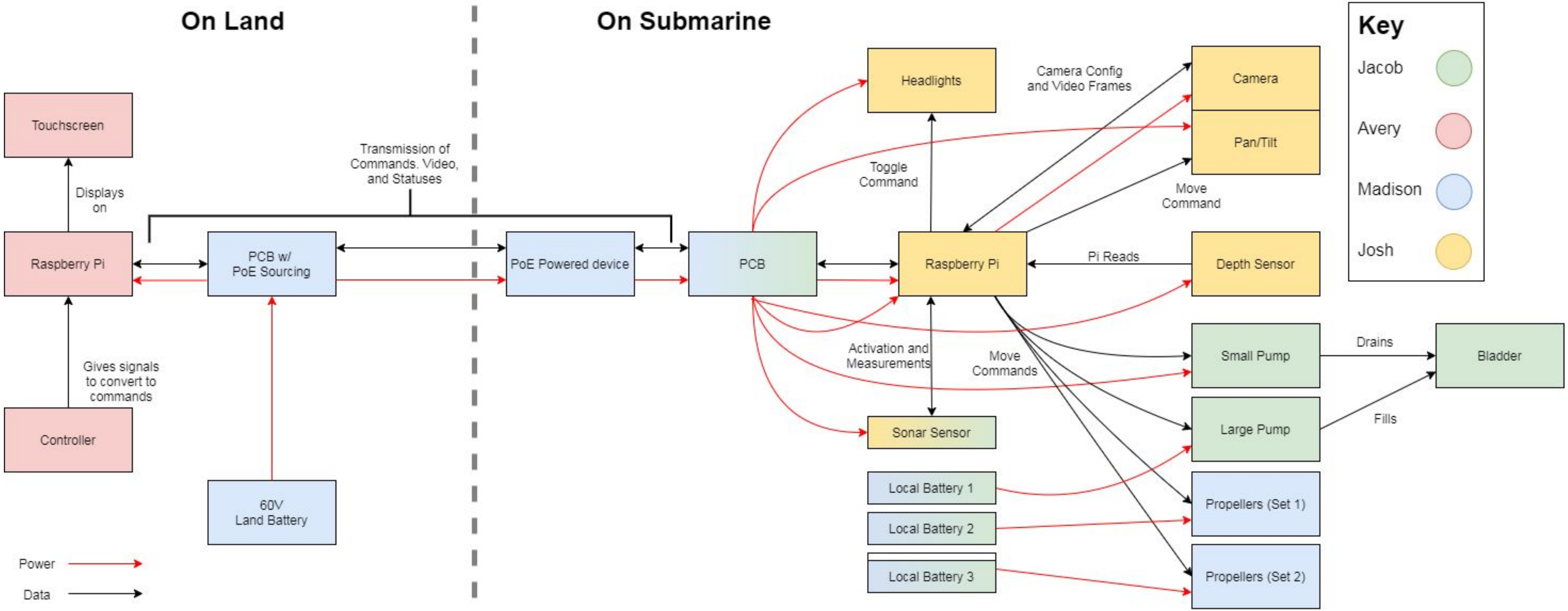
*Temperatures verified by datasheets.

Block Diagram



Design Approach and Work Layout

Work was split amongst group members based off of what key systems they felt capable of working on. The interplay between the major systems also necessitates and is used to show teamwork capabilities.

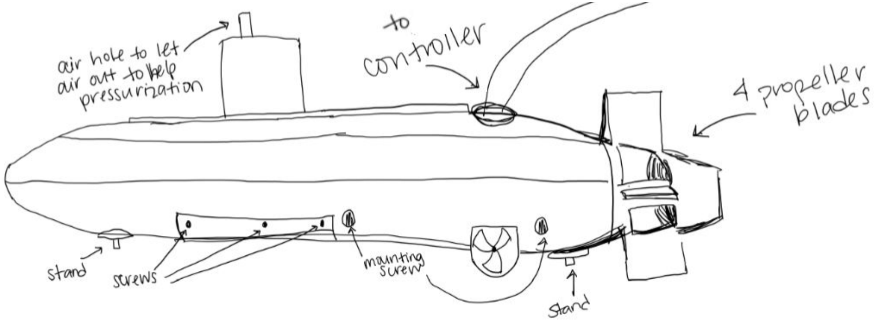


Work Layout

Major System	Primary Engineer	Secondary Engineer
Vision	Joshua	Avery
Movement	Madison	Jacob
Cabling and Routing	Madison	Jacob
Batteries/Power	Madison	Jacob
Ballast	Jacob	Joshua
Command / Control	Avery	Joshua
Hull	Joshua	N/A

Hull

Before electrical designs could be made for the ballast system, or special pieces made, calculations were done to verify if the combination of the artistic renderings below and the selected parts could be accommodated. This includes understanding the pressure that the hull must resist as well as how the shape and dimensions affect the buoyancy.



Dome

Here is an example of calculating the pressure on the most sensitive piece - the acrylic dome from EZTopsWorldWide. The remainder of the hull is comprised of a PVC pipe (rated for 160 psi) and custom 3D printed pieces which are thick enough to withstand the pressure.

Calculation of bucking pressure of an elastic thin spherical shell using a classic formula
White Paper: https://eprints.keele.ac.uk/1563/1/Stability.pdf

$E := 0.95\ \text{GPa}$ Value from Mat Web can vary for Acrylic's modulus of Elasticity from 0.0420-3.30 GPa

$v := 0.4$ Values from Mat Web for Poisson's ratio can varry from 0.370 - 0.430
http://www.matweb.com/search/datasheet_print.aspx?matguid=632572aeef2a4224b5ac8fbd4f1b6f77

$h := \frac{1}{16}\ \text{in}$ Use the thinnest point on the dome, which is the apex. See https://plastic-domes-spheres.com/plastic-domes

$R := 6\ \text{in}$

$$Pdif := \frac{(2 \cdot E)}{\sqrt{3 \cdot (1 - v^2)}} \cdot \frac{h^2}{R^2} = 18.8361\ \text{psi}$$

This excludes the air pressure above the water, which is assumed to equal the air pressure in the submarine.

Convert to depth ρ is water density ge is gravity acceleration. https://blog.prepscholar.com/what-is-the-density-of-water

$\rho := 1.02\ \frac{\text{g}}{\text{cm}^3}$ Valid for sea-water, yielding slightly less depth (Use 1.0 for fresh). Pressure varies less than 1% over range of 40F to 100F

$$Depth := \frac{Pdif}{(\rho\ g_e)} = 42.5966\ \text{ft}$$

Dome

The dome was ordered to be of a suitable thickness (0.25” avg.) to avoid breaching. Despite reading from other sources that the apex of the dome is the area most susceptible to breaching, there was reason to believe the dome would easily survive. This was seen in the demonstration and water testing. The company has a white paper on their site where they worked with students from the Puget Sound Naval Shipyard to conduct hydrostatic pressure tests on domes similar to our intended size. The dome they tested had a 10.16 cm (4”) diameter, a 0.635 cm (0.25”) thick flange, and was 5.08 cm (2”) tall. They noted that it could withstand pressure up until 600 psi, which would be a depth of 365 m (1200 ft), and is well beyond our desired testing range.

The calculations shown on the previous slide make assumptions about the material chosen, as the exact plexiglass used by the company isn’t advertised. The paper discusses a similar test ran on a dome made of lexan, which resisted until 579 m (1900 ft). Our dome has also been calculated with measurements meant to accommodate the size of the pan/tilt mechanism.

The white paper can be found here: https://www.eztopsworldwide.com/EZ-TOPS%20Dome%20Test.pdf

Buoyancy Calculations

The buoyancy of the submarine also had to be calculated. Purchasing heavy parts was ultimately desired due to a miscalculation discussed in the next slide. Under the belief that the submarine would sink with too heavy of parts, a portion of the electrical power was delivered from the on-land battery.

The displacement of the submarine was found by adding the total air volume and total solid volume of the hull components and dome, getting a weight from this and adding the weights of the internal components to get a final value.

Sub displacement in air = $\sum v_a \rho_a + \sum v_h \rho_h + v_d \rho_d + \sum w$

va = air volume
pa = air density
vh = solid hull volume
ph = solid hull density

vd = solid dome volume
pd = solid dome density
w = internal weights

On the right is a sample of the calculations, in this case it is calculating the weight of the dome and the air inside.

The submarine is buoyant by design, with neutral buoyancy achieved when the displacement in water equaled the displacement in air.

$dod := 5.25\ in$ dome outer diameter

$dfl := 0.5\ in$ Dome flange length

$dodwf := dod + (2 \cdot dfl) = 0.15875000\ m$ dome outer diameter

$dh := \frac{dod}{2} = 2.625\ in$ Dome "height" (flange included)

$dft := \frac{1}{4}\ in$ dome flange thickness

$dt := \frac{1}{16}\ in$ dome thickness

$did := dod - (2 \cdot dft) = 4.75000000\ in$ dome inner

$d\rho := 1.066\ \frac{g}{cm^3}$ dome density

$dav := \frac{\pi \cdot (did^3)}{12} = 0.0005\ m^3$ dome air volume

$fav := \pi \cdot \left(\frac{did}{2}\right)^2 \cdot dft = 0.00007260\ m^3$ flange air volume

$daav := dav + fav = 0.00053238\ m^3$ dome adjusted air volume

$dsv := \frac{\pi \cdot (dod^3)}{12} - daav = 0.00008842\ m^3$ dome solid volume

$fsv := \frac{\pi \cdot dft \cdot ((dodwf^2) - (did^2))}{4} = 0.00005309\ m^3$ flange solid volume

$tdsv := dsv + fsv = 0.00014151\ m^3$ total dome solid volume

$dw := d\rho \cdot tdsv = 0.15084650\ kg$ dome weight

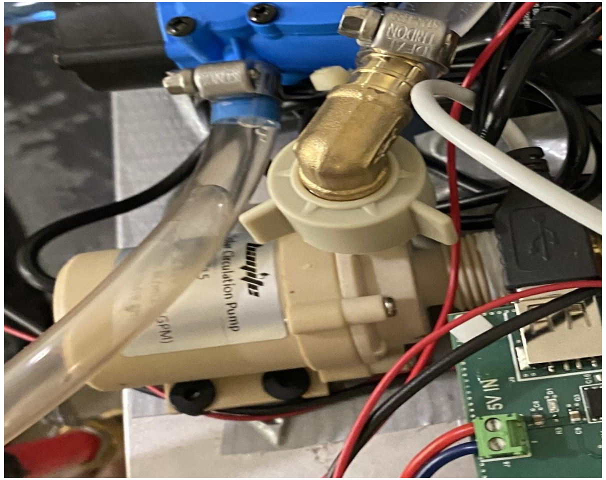
Miscalculation and Correction

When doing the calculations, a mistake was made regarding the total displacement of the submarine, and it was found that the submarine would be too buoyant. This was caught and corrected by increasing the static ballast on board. This took the form of 2-foot long #5 rebars, which fit underneath the deck used to mount the parts.

Movement (Ballast)

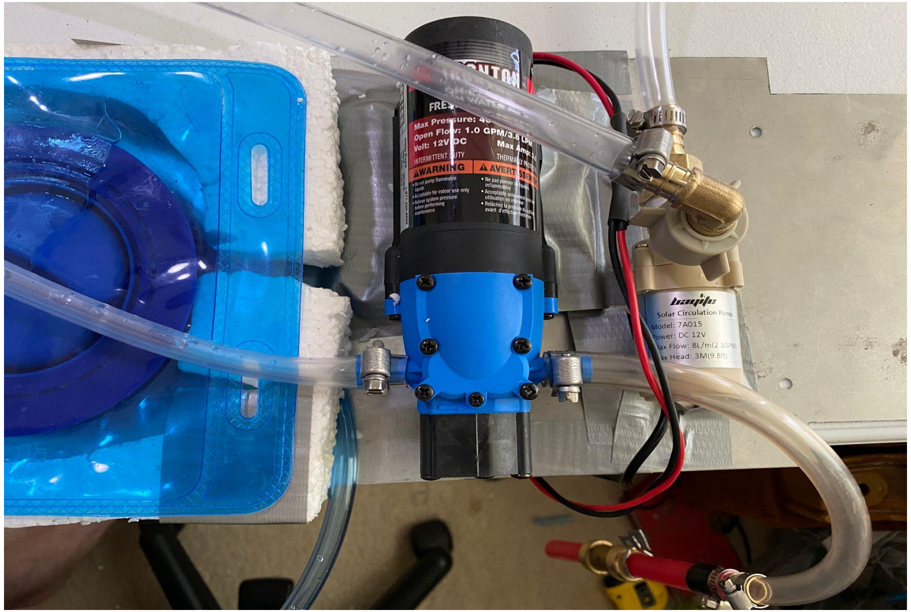
Once the buoyancy had been calculated, the bladder and pumps could be selected, and a system to fill the bladder and detect it’s fill status could be designed.

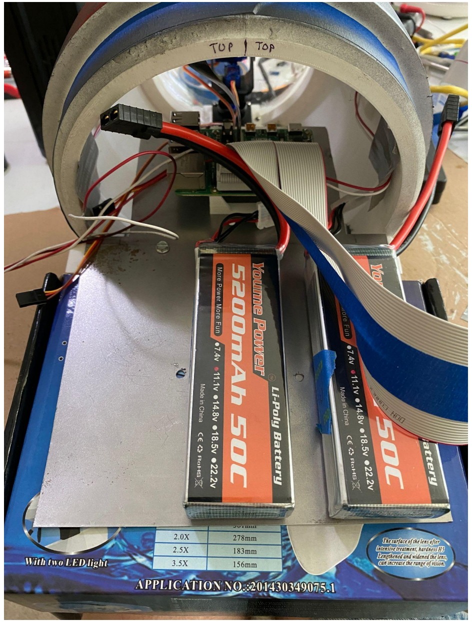
- Bladder needs to be sealed and easily drained/filled
- Pump needed to be able to fill the bladder



Movement (Ballast)

- Exfil pump needs at least 37 PSI force
- Higher Power requirement for stronger pump





Ballast Progress and Budget

Part	Cost	Purpose	Status
Bayite Circulation Pump 12V	$26.50	Inflow Pump	Acquired
Ironton 12V Pump	$52.99	Exfil Pump	Acquired
11.1V 5.2A/h Battery	$65.69	Exfil Pump Power Supply	Acquired
Bladder	$12.99	Bladder	Acquired

Movement (Propellers)

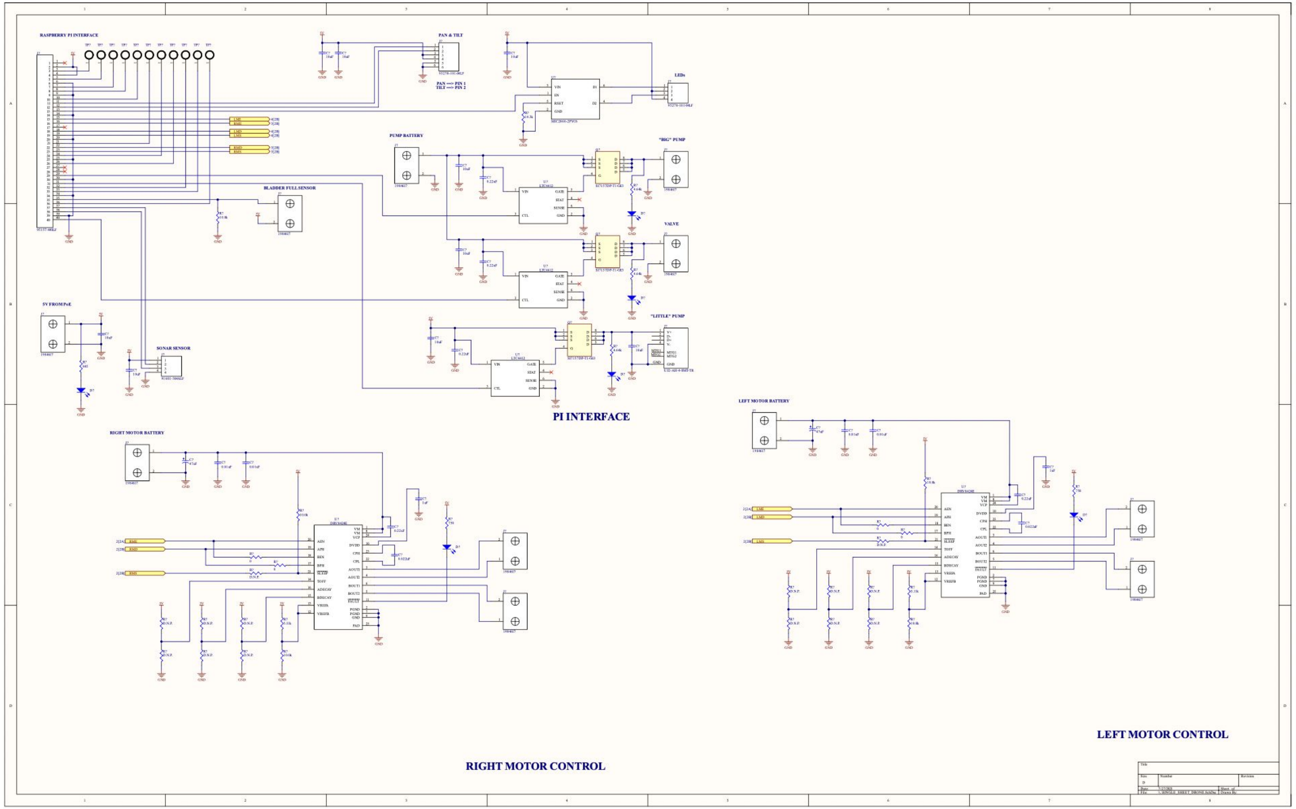
- Two sets of 2 motors
- Each set of motors is connected to the drone PCB, which has a Pulse Width Modulation circuit
- One battery per set of motors

Drone PCB

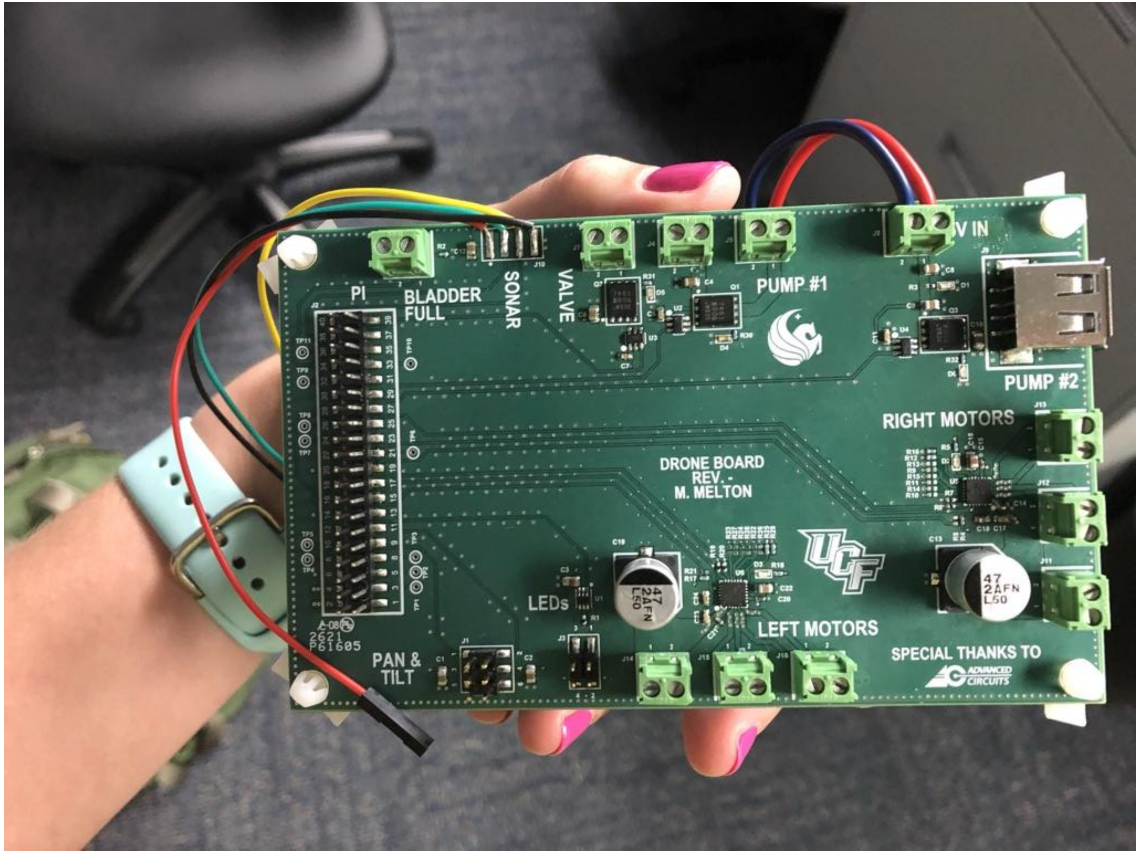
Madison's Budget

Part	Cost	Purpose	Status
Motors	$50 ($25/pair)	Propel drone through water	acquired
PCB (printing and parts)	247.78+13.74+28.75+6.79+28.75+134.33+101.33=$561.47	Allow controller to turn motors on/off	acquired
Batteries on board (3)	$120	Power motors and large pump	acquired
Youme Battery charger	$20	Charge batteries	acquired
Ethernet cable	$35	Allow data and power to be transmitted	acquired
Battery on land	$180	Power components	acquired

On-board PCB - Schematic



On Board PCB Actual



Droneboard PCB BOM

Comment	Description	Designator	Footprint	LibRef	Quantity
Cap	Capacitor	C?	RAD-0.3	Cap	52
Cap Pol2	Polarized Capacitor (Axial)	C?	POLAR0.8	Cap Pol2	1
150040AS73220	LED, Amber, SMT	D?	3.2X1.6X1.1	LED2	1
150040VS73240	LED, Green, SMT	D?	3.2X1.6X1.1	LED2	6
D Zener	Zener Diode	D?	DIODE-0.7	D Zener	2
Diode	Default Diode	D?	SMC	Diode	4
LED2	Typical RED, GREEN, YELLOW, AMBER GaAs LED	D?	3.2X1.6X1.1	LED2	2
MMSZ5233C-E3-18	Zener Diode	D?	DIODE-0.7	D Zener	7
SS-60300-010		J?		SS-60300-010	2
Inductor	Inductor	L?	0402-A	Inductor	7
Header 20X2	Header, 20-Pin, Dual row	P?	HDR2X20	Header 20X2	1
BUK7Y38-100E		Q?		BUK7Y38-100E	2
Res3	Resistor	R?	J1-0603	Res3	73
749020111A		T?		749020111A, HX5084FNL	2
LT8620		U?		LT8620	7
LTC4291-1		U?		LTC4291-1	1
LTC4292		U?		LTC4292	1

Power Over Ethernet

Source	Voltage	Current
Small ballast pump	5	0.17
Raspberry Pi	5	3
Flashlight	3.3	0.03
Pan/Tilt & sonar	5	6
Total	19 V	3.2 A

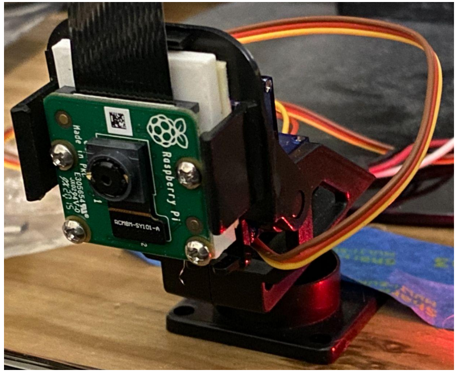
Figure 1: NEC 2020 Table 725.144 adjusted for 45°C ambient temperature

AWG	Number of 4-Pair Cables in a Bundle																	
	1-7			8-19			20-37			38-61			62-91			92-192		
	Temperature Rating			Temperature Rating			Temperature Rating			Temperature Rating			Temperature Rating			Temperature Rating		
	60°C	75°C	90°C	60°C	75°C	90°C	60°C	75°C	90°C	60°C	75°C	90°C	60°C	75°C	90°C	60°C	75°C	90°C
26	0.71	1.00	1.23	0.50	0.71	0.88	0.39	0.56	0.68	0.33	0.47	0.58	0.32	0.45	0.55	NA	NA	NA
24	0.84	1.19	1.46	0.57	0.82	1.01	0.45	0.64	0.79	0.39	0.55	0.68	0.33	0.46	0.56	0.28	0.39	0.48
23	0.88	1.25	1.54	0.63	0.91	1.11	0.54	0.78	0.95	0.47	0.65	0.81	0.41	0.58	0.71	0.32	0.45	0.55
22	1.06	1.52	1.87	0.74	1.05	1.29	0.54	0.78	0.96	0.47	0.67	0.83	0.44	0.63	0.77	0.37	0.51	0.62

Vision (Camera)

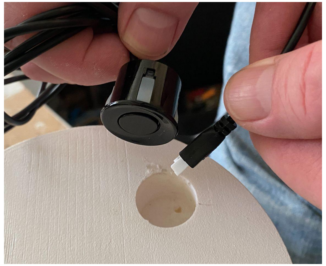
The Raspberry Pi Camera Module V2 was chosen for:

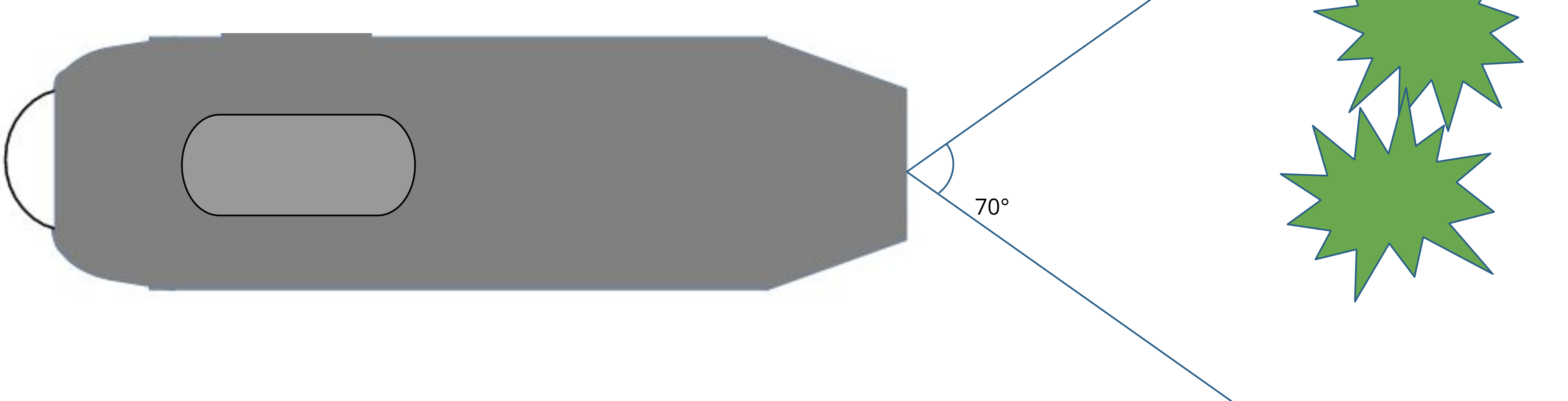
- Ease of interaction (it's meant for the Pi)
- Low price-point (less costly to replace)
- Small size (easily fits within submarine, and pairs with pan/tilt nicely)
- Capturing 1080p30 video
- Frames can be captured using the C++ version of the OpenCV library, and then transmitted via UDP to the controller.



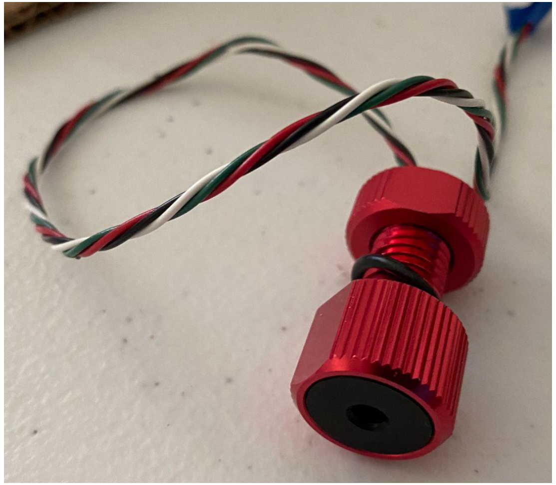
Ultrasonic Sensor

The sonar sensor used was the DFRobot SEN0208 Ultrasonic Sensor, which has a detection cone of 70° and an operating range between 0.25 - 4 meters. It is located at the rear of the submarine to detect any objects in the way when reversing.





Depth Sensor



This is actually a combined pressure and temperature sensor. It was bought from BlueRobotics due to being a combined sensor, it's great pressure range of up to 30 bar (300 m depth), it’s sturdy construction, high resolution of 2mm, and accessible via I2C. Temperature can be measured to within 1°C. The I2C sensor is accessed via libraries from the Raspberry Pi’s chip manufacturer, as well as C++ code derived from the GitHub repository found here: https://github.com/TEConnectivity/MS5837_Generic_C_Driver

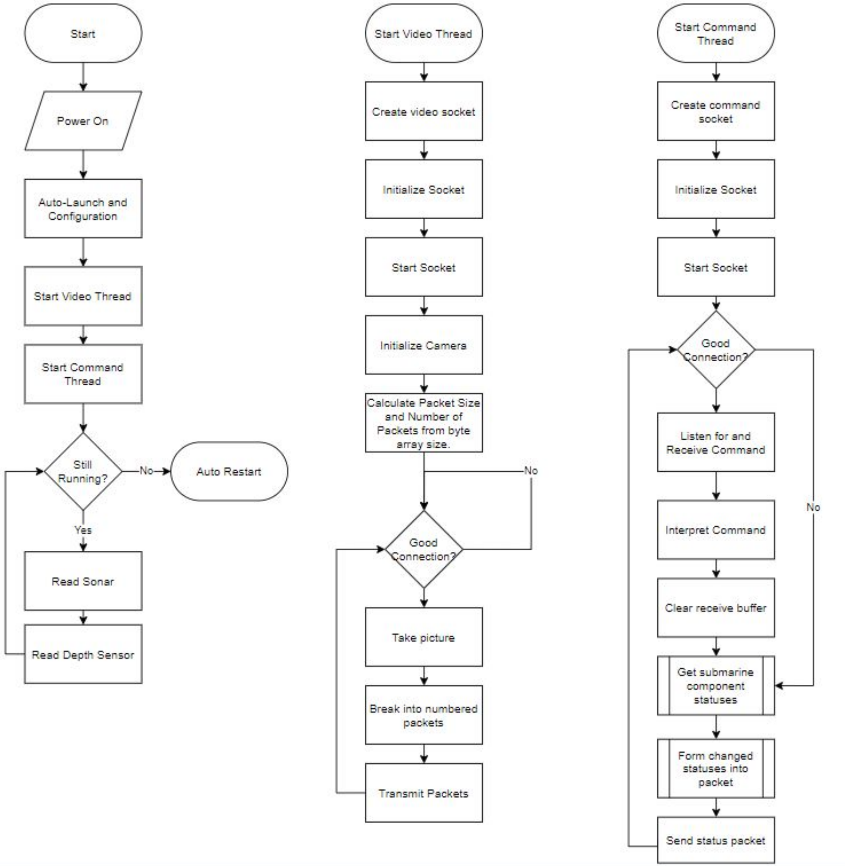
Raspberry Pi

The Raspberry Pi 4B+ was selected for its compatibility with the Raspberry Pi Camera Module v2 along with its gigabit ethernet capabilities and multiple interface types (USB, HDMI, MIPI-CSI). Additionally, the Raspberry Pi is well supported, and its size and price point were also influential in its use inside both the submarine itself and when paired with the controller.

Additionally, the Raspberry Pi was chosen over microcontrollers due to the flexibility that the OS provides. We use Raspbian on both Pis, and as such are given:

- Greater programming language freedom
- Use of potentially cross-language libraries (especially when dealing with GPIO)
- The use of existing libraries
- Optimized thread handling and networking
- The ability to virtual desktop into either Pi should diagnosis be needed during testing (Invaluable)

Software Diagram (Submarine)



UDP

The submarine utilizes UDP to communicate to the controller. UDP is well known for being a fast, “fire and forget” protocol, which serves as the foundation for the more sophisticated Real-time Transport Protocol (RTP). This is ideal, as priority lies in the controller receiving image data and the submarine receiving command data in their respective sockets.

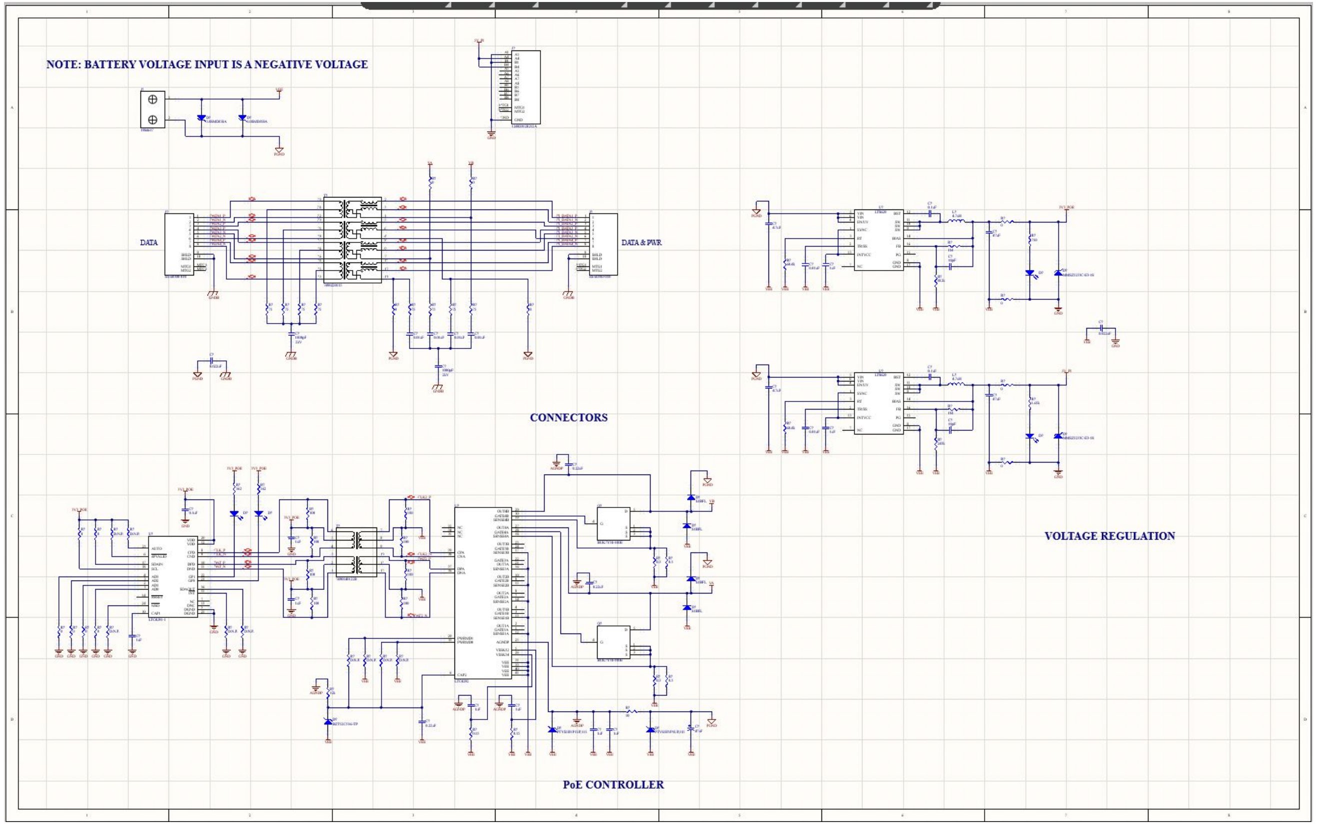
No time is lost with acknowledging sets of packets, as packets are sent in character arrays containing their packet numbers. These can then be directly inserted into the image, meaning any lost data can be quickly overridden by the next incoming packet set. A similar setup has been used for the transmission of submarine component statuses such as the pumps, as well as the commands being received by the submarine.

The images must be broken down into sets of packets due to the size of the images being much larger than the maximum size of data allowed in a packet - just under 64 KB. However, calculations are performed in the program to determine the maximum amount of data that can be transmitted at a time to result in a whole number of packets. Dealing with a whole number simplifies packet transmission and assembly schemes, as the final packet doesn’t have to be specially treated (if the remaining image data needed to be extracted from a significantly larger packet).

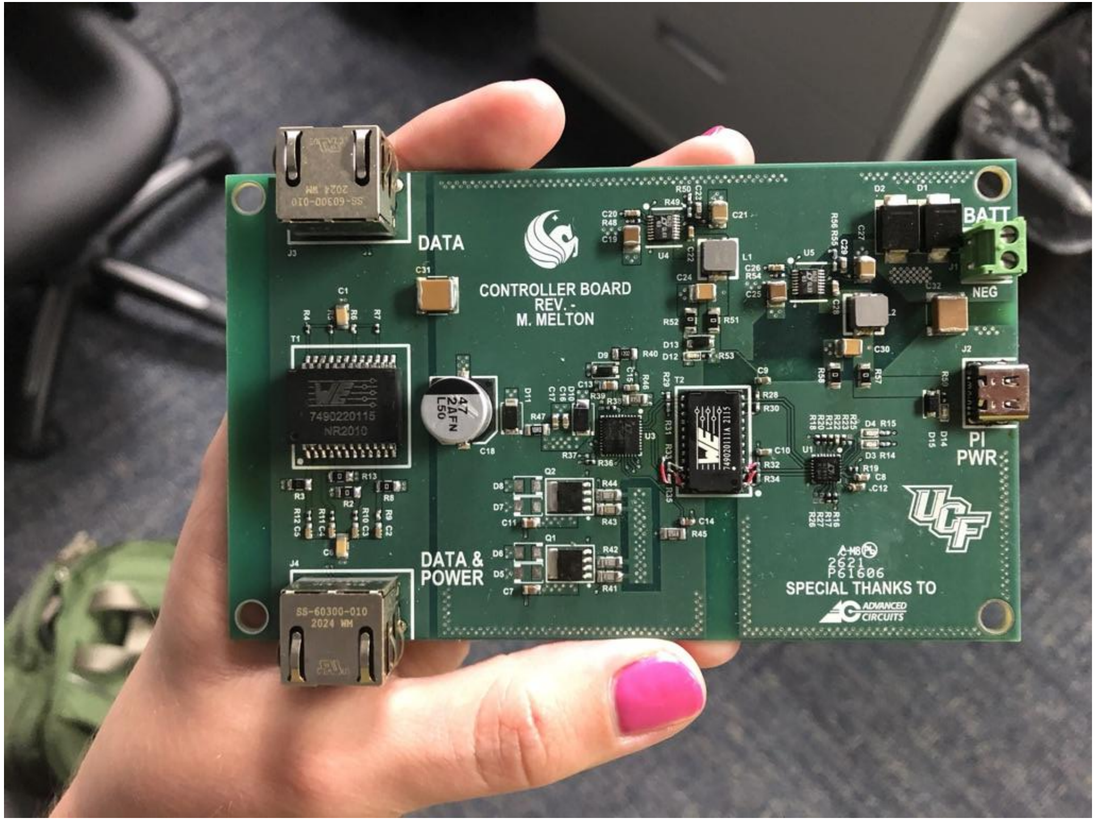
Why wired?

- Wifi signals can't penetrate the water!
  - Only low frequency or very low frequency transmissions can get through, and are typically not suitable for image streaming. This is because of the poor bitrate which is on the order of hundreds of bits per second, HD pictures require at least megabytes.
  - MIT's 2018 work on the subject was not successful past 3.5 meters underwater, and did not work well in rough waters (like the ocean).
- The submarine needed to be easily retrievable. The wire and rope can be easily pulled in to shore.
- Use of a buoy out in the water to extend the range would necessitate a way to retrieve the buoy anyway.
  - Buoys out in the water can float away and become a surface level hazard to ships and swimmers.

Land PCB Schematic



Land PCB Actual



Land Board BOM

Comment	Description	Designator	Footprint	LibRef	Quantity
47uF	Polarized Capacitor (Axial)	C?	POLAR0.8	Cap Pol2	1
Cap	Capacitor	C?	RAD-0.3	Cap	17
5.0SMDJ58A	Zener Diode	D?	DIODE-0.7	D Zener	2
150040VS73240	LED, Green, SMT	D?	3.2X1.6X1.1	LED2	2
BZT52C5V6-TP	Zener Diode	D?	DIODE-0.7	D Zener	1
PTVS58VP1UP,115	Zener Diode	D?	DIODE-0.7	D Zener	1
PTVS58VS1UR,115	Zener Diode	D?	DIODE-0.7	D Zener	1
S1BFL	Default Diode	D?	SMC	Diode	4
1984617		J?		1984617	2
SS-60300-010		J?		SS-60300-010	2
BUK7Y38-100E		Q?		BUK7Y38-100E	2
Res3	Resistor	R?	J1-0603	Res3	39
749020111A		T?		749020111A, HX5084FNL	2
LTC4291-1		U?		LTC4291-1	1
LTC4292		U?		LTC4292	1

Software Diagram (Controller)

Xbox Inputs

A – Float Up

B – Turn on/off Flashlight

X – Prime Ballast

Y – Sink Down

Left Joystick – Submarine Movement

Right Joystick – Camera Movement

D-Pad – Flashlight modes

Start – display sub info

Select – Display time and FPS

LB – Screen Brightness down

RB – Screen Brightness up

Controller PI

Reads the inputs from the xbox controller then packages them to be sent to the on-board Pi.

SSH/UDP

The packaged information would then be sent via the serial connection in ideal rates of every 1 to 5 ms.

Submarine PI

The submarine Raspberry Pi decodes packages and then respectively controls the GPIO ports

Submarine Outputs

The submarine will always output video through packets, but statuses such as if the bladder is full or empty will be sent back in the form of packets as well.

Controller Design

Why Not Make Our Own Controller?

The reason for using an aftermarket controller instead of creating a new controller is because the aftermarket controller allows us to enable touch screen sensitivity on the display and add more inputs rather than limiting the Raspberry Pi I/O to only capturing touch input.

What is the significance of the touch-screen?

The reason the design maintains the touch screen sensitivity as a priority is because it allows for software interactions such as button inputs via the screen or dials displayed slightly transparently over the submarine imagery.

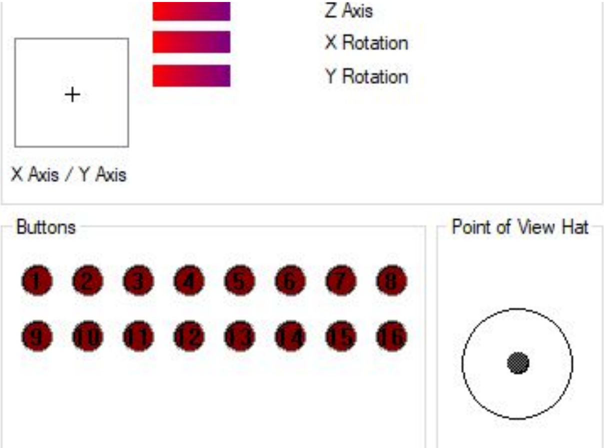
Initializing the Xbox Controller to the PI

1. Initialized the Pi to the most recent Raspbian using the commands:
   a. `sudo apt-get update`
   b. `sudo apt-get upgrade`
2. Install the driver that connects the controller and the Pi:
   a. `sudo apt-get install xboxdrv`
3. Establish the controller as the mouse of the Raspberry Pi:
   a. `sudo xboxdrv --detach-kernel-driver --silent --mouse`
4. The mouse commands become:
   a. **A –** Left click, **B –** Right-click, **X –** Middle mouse click, **Y –** Enter, **Left Joystick –** Mouse movement, **Right Joystick –** Scroll wheel, **D-Pad –** Arrow keys, **Start –** Forward, **Back –** Back, **LB –** Page up, **RB –** Page down

Under the circumstances the xboxdrv does not support the controller as a xbox device the program will still boot up naturally and touch screen will be available however the controller most likely won't act as a mouse but it does depend on the brand of the controller.

Controlling the Submarine Pi on Land

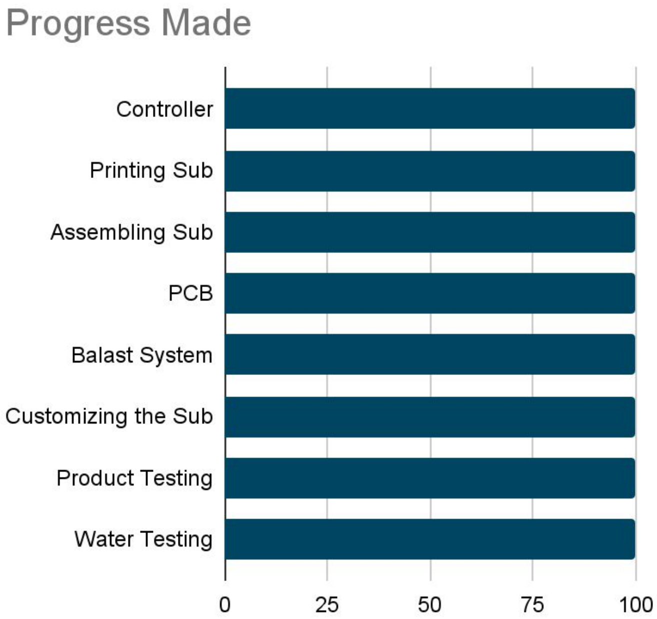
- Using a similar process to that of the windows software we can track the controller inputs being received and send them to the Submarine.
- The Controller input process conjoined with pigpio software allows for us to directly control the GPIO pins of the Submarine Pi from the land controller.
- This process is initialized by scripts thats run on bootup for both sides and allow the two entities to connect to each other without human initialization meaning any can power and play the device.



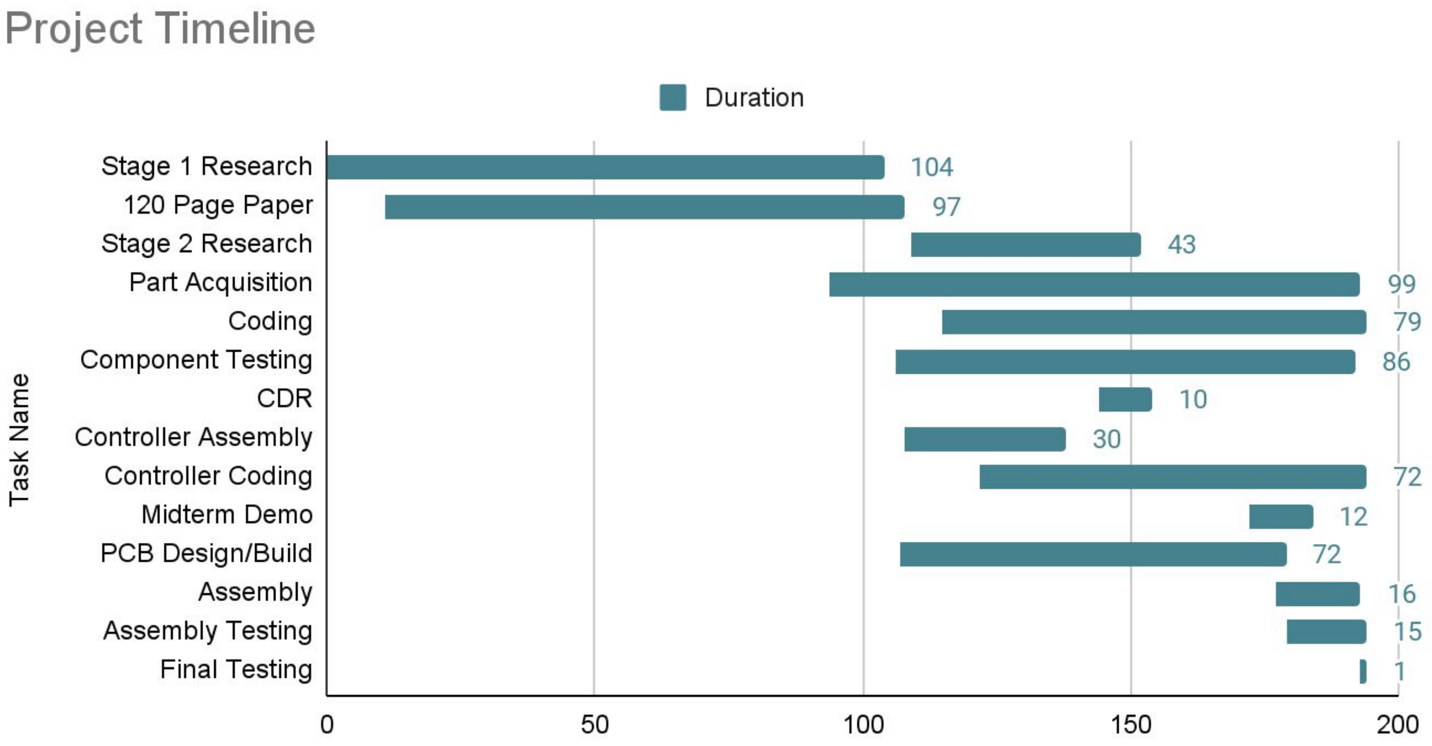
Project Progress Chart

- The progress of the project maintained constant growth in order to maintain deadlines.

- The process of splitting the Submarine into parts then compiling it together to have one full system worked to complete the large project within time.



GANTT Chart


Project Timeline
Duration
Task Name
Stage 1 Research
120 Page Paper
Stage 2 Research
Part Acquisition
Coding
Component Testing
CDR
Controller Assembly
Controller Coding
Midterm Demo
PCB Design/Build
Assembly
Assembly Testing
Final Testing
104
97
43
99
79
86
10
30
72
12
72
16
15
1
0
50
100
150
200

Total Budget Chart (pt. 1)

Submarine Components					
Item	**Purpose**	**Weight/Item**	**Price/Item**	**Price Allotted**	**Price for Parts**
Controller				$250.00	
Controller + Parts	controller	17.24 ounces	NA		$86.64
Raspberry Pi	controller	1.76 ounces	$75.00		$75.00
Total spent :$161.64	Budget left:$88.36				
PCB				$250.00	
Batteries*	Motors,Pi's,Sub	82.89 ounces	$120.00, $180.00		$300.00
Ethernet Cable	Transfer Power/Info	N/A	$35.00		$35.00
PCB + parts	Controls power flow	10.58 ounces	N/A		$561.47
Motors	Propulsion	2.64 ounces	$25		$50.00
Battery Charger**	Charge Batteries	25.57 ounces	$20.00		$20.00
Total spent :$966.47	Budget lost:$-716.47	After controller budget gain there is $-628.11			

*Includes land battery, **Part of support equipment

Total Budget Chart (pt. 2)

Submarine Components					
Item	**Purpose**	**Weight/Item**	**Price/Item**	**Price Allotted**	**Price for Parts**
Ballast				$250.00	
Baylite pump	Inflow pump	10.56 ounces	$26.50		$26.50
Irontron 12v pump	Exflow pump	28 ounces	$52.99		$52.99
11.1V 5.2A/h Battery	Exfil Pump Power Supply	12.66 ounces	$65.69		$65.69
Bladder	Bladder	6 - 70 ounces	$12.99		$12.99
Total spent :$158.17	Budget left:$91.83	After controller+PCB budget gain there is $-536.28			
Submarine				$250.00	
Sub shell Parts	Contain Parts	50.74 ounces	$29.31, $30.00		$59.31
Camera + Pi	Send live feed	1.41 ounces	$75.00, $29.95		$84.95
Pan tilt mechanism	Allows for camera movement	1.05 ounces	$6.95		$6.95
Extra sensors	Monitor distance	1.76 ounces	$1.00, $72.00, $15.00		$88.00
Acrylic Dome	Viewing dome	5.29 ounces	$34.50		$34.50
Rebar	Counter Weight	83.44 ounces	7.38		$126.35
Total spent :$400.06	Budget left:$-150.06	After controller+PCB+Ballast budget gain there is $-686.35			Total spent: $1686.35

What Went Right What Went Wrong

Right

- Most of the planned functions of the sub worked when demonstrating inside of the water.
- The land tests were entirely successful.
- The sub maintained structural stability at 3 meters of depth over a prolonged period of time.
- The vision system exceeded performance expectations with higher frame and transmission rates.

Wrong

- Poor communication between team members led to assumptions and incorrect parts and sub-assemblies.
- Part acquisition and assembly took longer than expected.
- Poor weather conditions delayed testing.
- Poor initial sealing led to leaks in the submarine.
- The initial budget of the project was exceeded.

Things We Would Change In the Future

- The way the sub could be accessed
- The size and weight of the sub could be reduced to smaller proportions
- Adding an internal sub camera to show status of the inside
- Change the controller to a custom designed rather than aftermarket controller with a mount
- Changing the ballast system from limited bag size and having a sensor to detect the amount of air and water inside the bag.
- Change the sonar system in the back (can’t understand in 3D environment)

Thanks for Watching!