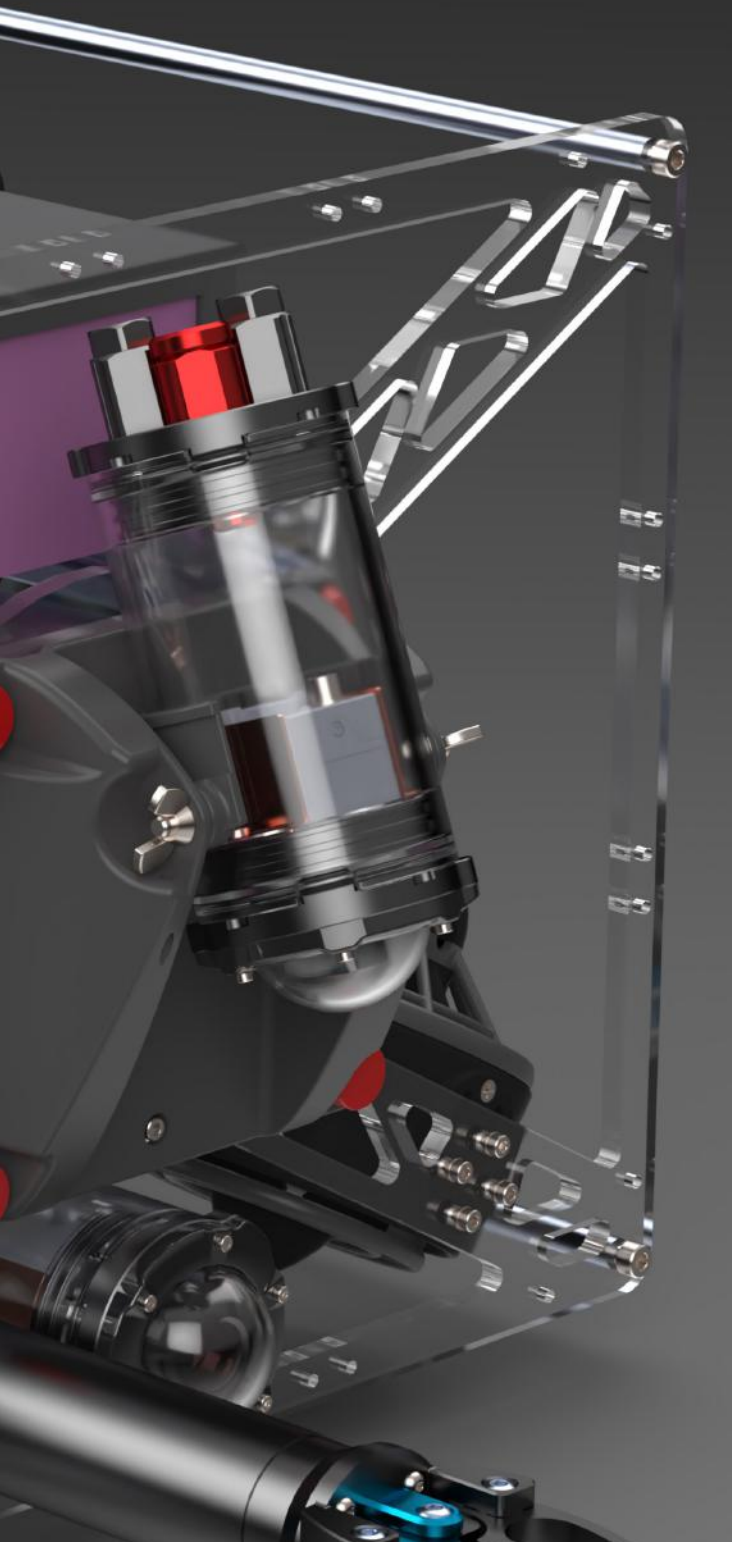
Robosharks

Technical Report



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Ryan Barnes Mechanical

Fiona Gettelman Mechanical

Carter Harllee Mechanical, Props

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MATE Word Championship 2022

Robosharks

Boulder High School

Boulder, Colorado, USA

Figure 1: Robosharks Team (1/2)
Left to right: Amitan Bar-Evan, Bryce Irving, Mikael Steinman, Carter Harllee.

Figure 2: Robosharks Team (2/2)
Left to right: Ryan Barnes, Fiona Gettelman, Ian Soledade.

Abstract

The Robosharks is a company from Boulder High School, Boulder, Colorado, founded to develop outside-of-the-box solutions to various underwater problems. The Robosharks is composed of four returning members and three new members, each with a passion for robotics and design. Additionally, our company houses a Navigator subteam, where we train our new members. The Robosharks are presenting the Boxfish for this year's RFP.

The Boxfish is designed to be easily serviceable and modular, and we developed each of the ROV's components to fit these criteria. The frame allows for customizable configurations of our off-the-shelf manipulator. Two industrial cameras provide high-quality, low-latency video that assists in piloted ROV operation and autonomous computer vision tasks. Finally, we have a custom float with a buoyancy engine to complete profiles of the Antarctic waters.

The Boxfish uses optimized software to give the pilot precise control over all six degrees of motion. Additionally, the Boxfish has an intuitive graphical user interface to assist in ROV operation.

Although we are still picking up pieces of PVC off the pool floor, the Robosharks hope that the Boxfish will further inspire the global effort to solve the United Nations Sustainable Development goals.

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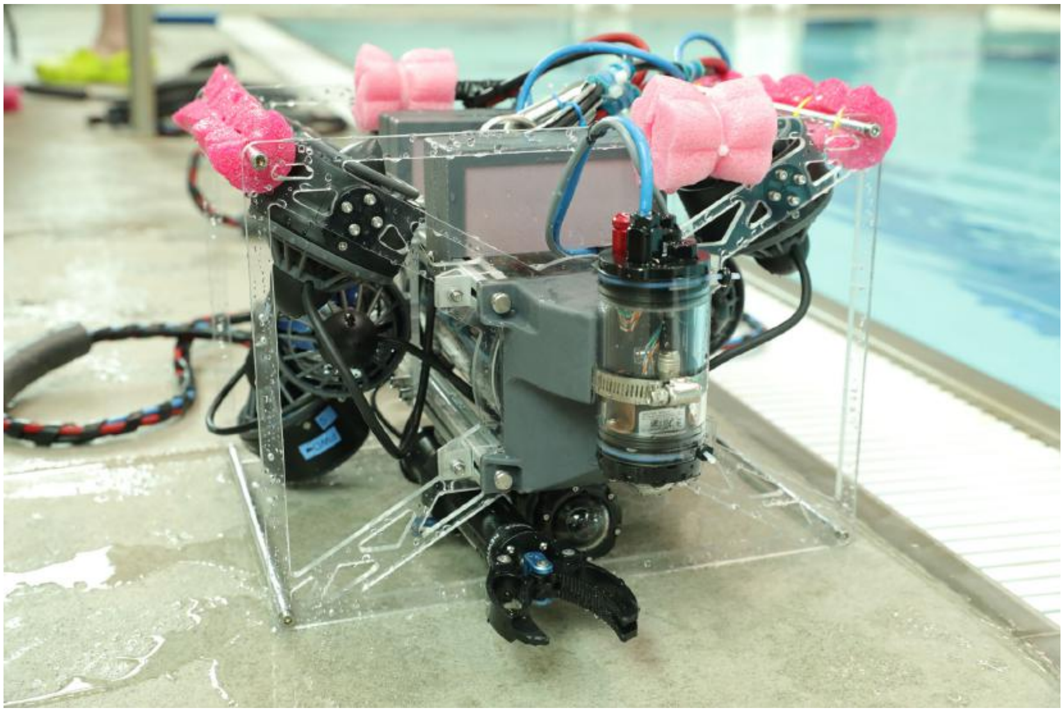


Figure 3: The Boxfish

Engineering Design Rationale

Innovation and Problem Solving

The first step in our design was to calculate a thruster layout that optimizes our degrees of motion. We developed a software tool we call TAU (Thruster Arrangement Utility) to quickly prototype and characterize the performance of a variety of thruster layouts. We took this layout and designed a frame and electronics enclosure around it. From there, we evaluated what other tools the ROV needed, and modified the frame to accommodate the extra payload. Our team researched cameras that would have minimal latency. We determined what electronics to use on board the ROV and the most space efficient packing of them inside the ROV, keeping in mind how our electronics choices would affect our software.

For each problem that arises, we use the same general system to work through the issue. The first step is always to find the root cause of the problem. This is an important step, because without it there is no way to know how serious the issue is or how to proceed, so we always make sure to start by focusing on diagnosing the problem's cause. Once the underlying issue of the problem has been identified, we can then move on to discussing a solution. After that, we make the proposed changes and start testing. Based on the results of our tests, it is often necessary to repeat this process multiple times until we are left with a thoroughly tested and reliable product.

A major issue we had with last year's ROV, the Hammerhead, was that both endcaps on the electronics enclosure were not securely held in place. This caused them, on two separate occasions, to disconnect from the tube, flooding the electronics. To avoid this happening again, we redesigned the ROV's frame and manufactured custom endcaps that bolt to the frame. Because of this, we no longer have to worry about a flood on the scale that we dealt with last year, and it has left us with a more robust and reliable vehicle.

During our first full enclosure test, in a member's bathtub, we had a major leak from the back endcap. After further testing, the leak was determined to be coming from the cable penetrators. As it turns out, most of them had not been done correctly, and so did not make a proper seal around the cables. With the issue identified, we were then able to redo all of the cable penetrators, and additional testing proved that the leak had been fixed.

Another issue we ran into, while not strictly part of the ROV, was with manufacturing the polycarbonate components. We cut these parts with a table CNC router, but the bit broke about a third of the way through the cut. After buying a new bit and trying again, we were met with the same issue. This prompted us to take a closer look and do some testing, which revealed that the polycarbonate sheet was not securely held to the machine bed. This caused it to vibrate, which put tremendous stress on the bit, causing it to break. With this new information, we used more screws to secure the sheet and were able to successfully cut all the remaining components.

Mechanical

The overall mechanical design was influenced by two major constraints we set early on: our choice and placement of enclosure, and our thruster layout. Other important design goals were easy modifiability, simple fabrication, and durability during transport.

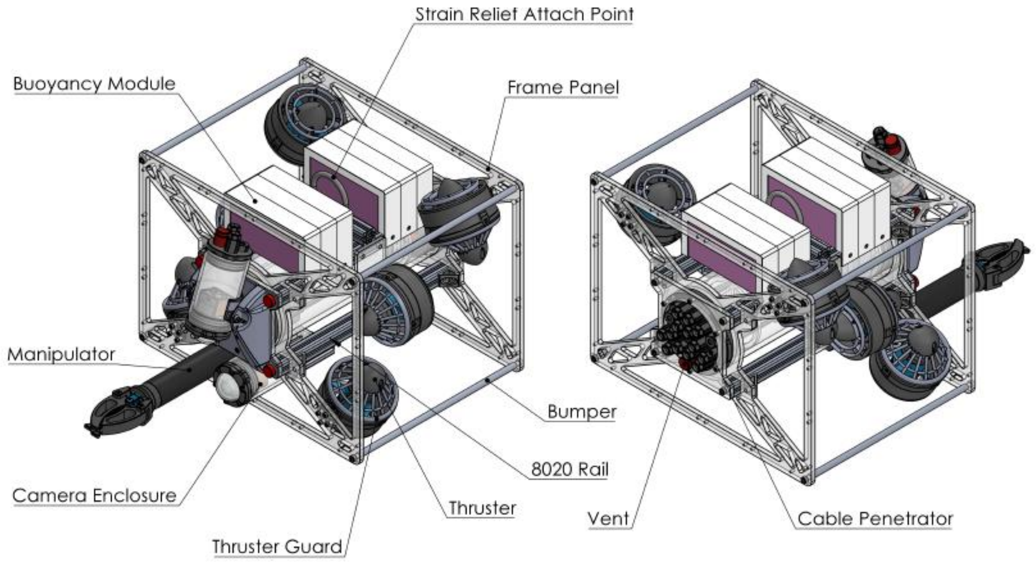


Figure 4: An overview of the mechanical design of the Boxfish

Main Enclosure

The single largest functional component of our design is our main enclosure. The main enclosure is a 115mm OD, 350mm long tube with endcaps on either end from Blue Robotics, and it encloses and waterproofs the bulk of our electronics. This size is the smallest, lightest, most hydrodynamic, and most cost effective size that can hold all of the onboard electrical systems necessary to power and control the ROV. However, it has a few modifications that make it differ slightly from a COTS enclosure: one of the end plates is replaced with a custom-machined one, and a similar custom-machined flange is added to the other. These plates serve as mounting points for the bars of 2020 t-slot aluminum extrusion (AKA 8020) that prevent the endcaps of our enclosure from falling off, as well as mount the enclosure subassembly to the rest of the frame. Electrical cables enter and leave the enclosure by means of waterproof cable penetrators from Blue Robotics.

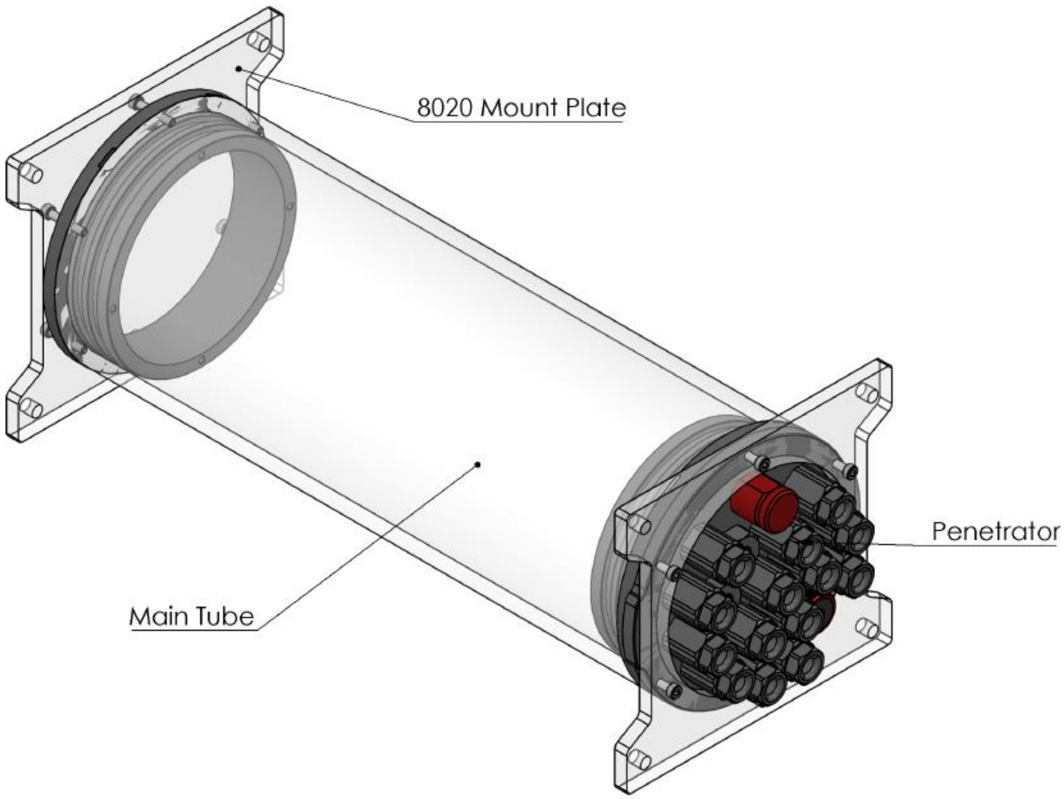


Figure 5: Main electronics enclosure

Thrusters

One of our earliest and most influential design constraints was the thruster layout. Our goals while creating this layout were high forward speed, high vertical lift capability, and 6-degree-of-freedom control. In order to achieve this, we reused 6 Blue Robotics T200 thrusters that proved to be reliable, powerful, and waterproof. To determine our layout, we collaborated with Robosharks alumni Noah, now a member of CWRUbotix, to write a program in Python called Thruster Arrangement Utility (TAU). After inputting a desired thruster arrangement, TAU iterates through each possible direction and rotation in 3-dimensional space and finds a maximum thrust in that direction or maximum torque around that axis. This program allowed us to rapidly iterate through and characterize the behavior of a variety of thruster arrangements until we determined our optimal thruster layout seen in figure 6. This layout, using only 6 thrusters, gives us excellent maneuverability as well as high surge and heave thrusts, allowing us to move quickly and lift heavy loads. The layout was also designed to prevent the plumes from each thruster from impinging on the vehicle.

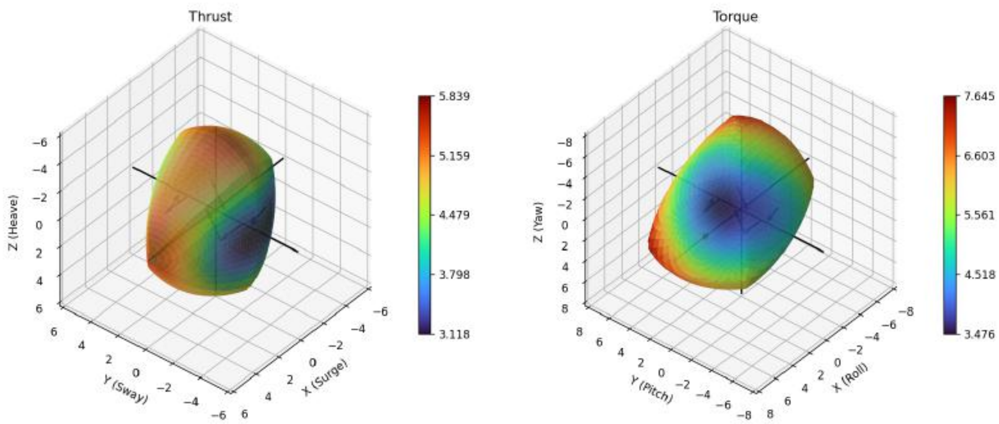


Figure 6: Thrust and torque space of the Boxfish as shown by TAU

Frame

The ROV frame serves two major purposes: it functions as “connective tissue” between our major functional components (main enclosure, thrusters, etc.) and as a protective box to prevent damage to more delicate components. It also prevents the vehicle from getting snagged or caught on any objects in its environment. We constructed the frame out of two polycarbonate panels and aluminum rods. The panels were machined in-house using a CNC router table at Boulder High School. These plates are relatively simple to manufacture, provide easy mounting points for our thrusters, and limit ROV damage from unexpected impacts. The plates are secured to each other using aluminum rods. The 8020 extrusions that hold the frame and the main enclosure together also serve another purpose: they provide highly adaptable mount points for any additional components we need to add to the vehicle. All of our cameras, manipulators, and buoyancy devices mount to the 8020.

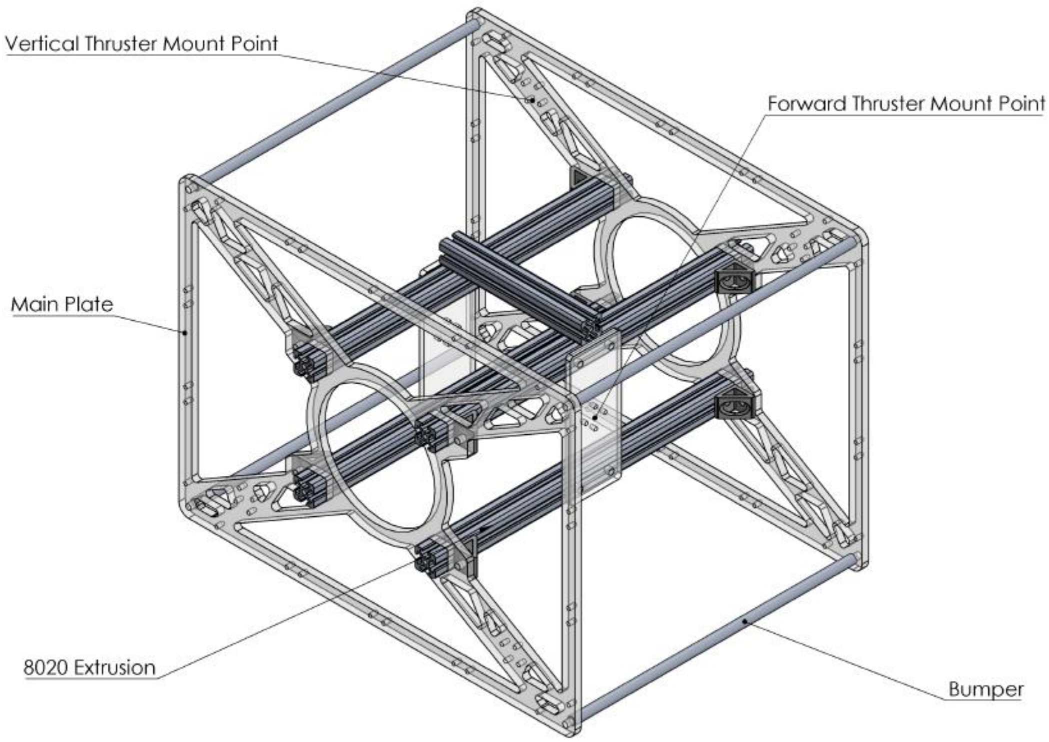


Figure 7: The external frame of the Boxfish

Outboard Cameras

The cameras are mounted in external enclosures in order to give us more control over their positioning and field of view. Our main camera is mounted underneath the ROV, next to our manipulator. It gives us our forward view. The second camera is mounted at the front of the ROV on a hinge and looks downwards at a slight angle. Our cameras are positioned such that they can see the end of our manipulator, yet are not obstructed by the main body of the ROV, giving us excellent situational awareness to approach tasks from numerous angles.

The cameras themselves are FLIR Blackfly IP camera modules. They communicate over Ethernet, and are powered off of 12v. Each camera is housed in an external enclosure (figure 8), and gives us low-latency, high quality video. The cameras are pointed through a domed port on the front of the enclosure to prevent image distortion, and we chose wide-angle lenses for a large field of view. The camera modules emit a significant amount of heat, so in order to keep our thermals in check, the camera mounting brackets are made of high thermal conductivity copper. This copper is mounted to the metal endcaps of each enclosure, allowing heat to conduct easily into the surrounding water.

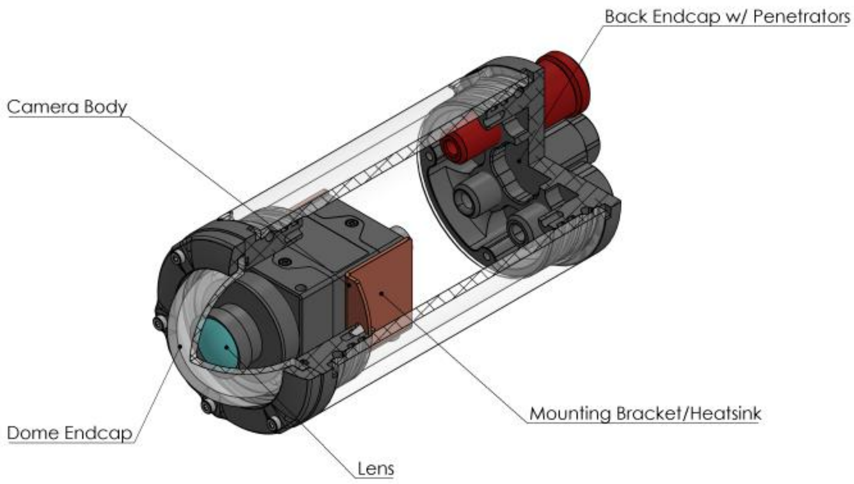


Figure 8: A cutaway diagram of the Boxfish's camera enclosure

Buoyancy

The next major aspect of the ROV we considered was its buoyancy. Unadjusted, the vehicle is negatively buoyant, meaning it's heavier than the volume of the water it displaces, and thus sinks. We needed to add low density material to the ROV to increase its volume without significantly changing its mass so that it reached neutral buoyancy. To achieve this goal, we designed and printed custom holders for foam insulation (buoyancy blocks). These buoyancy blocks are mounted to the t-slots on the ROV frame and are easily adjustable to fine-tune the ROV buoyancy after each small design change. The positioning of these blocks above the center of mass (CoM) was critical because it moved the center of buoyancy (CoB) upwards. Having the CoB above the CoM causes the vehicle to self-correct its orientation, making it much more stable.

Electrical

The single biggest impact on our electrical system was the decision to communicate with the vehicle over a single Ethernet cable. Due to this design decision, we only need one connection point to our topside computer. It also makes our tether more flexible and lightweight, and it eliminates points of failure.

Tether

The Boxfish's tether is incredibly simple. It consists of two 8-gauge power conductors and a single Ethernet cable. The cables are wrapped in a sheath to protect them and keep them bundled together. Blocks of foam are placed intermittently around that sheath, in order to keep the tether neutrally buoyant.

On-Board Electronics

The second-biggest influence on our electrical system was the decision to move all of our computing power topside. This meant we only needed a simple microcontroller on board the vehicle: an Arduino MKR with an Ethernet shield. This Arduino controls 6 Blue Robotics Basic ESCs (electronic speed controllers), which provide variable-speed and reversible control to each thruster. We have three separate Ethernet devices (the Arduino and two cameras) that need to communicate with the surface, so we needed to install an ethernet switch on-board the vehicle. Our thrusters and cameras are powered directly from the 12v coming off our tether, while the rest of our electronics require that we step the voltage down to 5v using a voltage converter.

Topside Electronics

Our topside electronics consist of a laptop and Xbox controller that communicate with the onboard electronics via ethernet, as well as two external monitors to give our pilot additional information. All of the heavy computing is done by the laptop.

Control System

Control Box

The control box is made out of a Condition 1 waterproof case, 8020 t-slot aluminum extrusion, and an MDF panel. The control box houses the Dell Latitude E7470 control laptop, two 10 inch monitors, and a multi-socket power strip. The power cables on the tether connect to the MATE provided power supply and the ethernet cable connects to the control laptop. We chose this control box design because it is compact and easily portable, and gives the pilot and copilot enough screen space to display all the necessary video and sensor data. An Xbox controller connects to the control laptop and gives inputs to control the thrusters and manipulator. We used an Xbox controller because it is small and easily transportable as well as intuitive to use.

Control Software

Our control software has two main purposes: control the ROV and display live video. Our control software is built to allow our ROV to use its full range of speeds without ever drawing over 25 Amps current. Please refer to figure 9 for a diagram to go with the following description:

First, the direction is obtained from the Xbox input. The net force from the thrusters is then maximized in that direction. Then they are scaled back down by the magnitude of the input direction. Now, the PID corrections are added to the scaled down thrusts. Then these combined thrust values are scaled down again to be within the current limit. A list of PWM values is built using the thrust list and T200 data provided by Blue Robotics. Finally, the manipulator signal is appended to the PWM list and sent to the Arduino.

The Arduino-side code is incredibly simple. It reads commands over Ethernet, acts upon them, and sends information from its sensors back. It also performs a few rudimentary safety checks to prevent the robot from behaving in an unsafe manner if communications are lost.

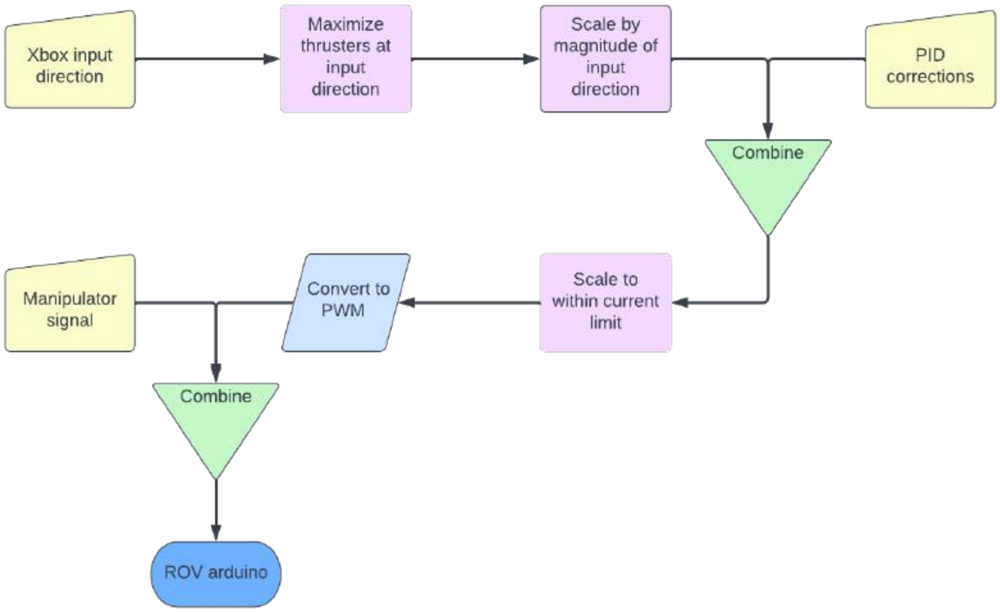


Figure 9: An overview flowchart of our control software

GUI

The GUI is created using PyQt5 and is critical to the functionality of the ROV. First, the GUI displays the sensor data and live video. The GUI also takes user input in the form of on-screen buttons that allow the driver to switch between navigation modes as well as reset the pitch trim. Finally, the GUI lets the ROV copilot launch and complete all computer vision tasks in the same application.

Payload and Tools

Manipulator

In order to interact with props, we have a Blue Robotics Newton Subsea gripper mounted to the bottom of our robot. This gripper is mounted in a way that allows us to rotate it between horizontal and vertical positions easily, meaning that we can use it in the most effective configuration for multiple different types of tasks. It can also fold further into the frame for easy storage and transport. We mounted neodymium magnets to the outer side of the manipulator to easily interact with metal pins without interfering with the functionality of the claw.

Float

For one of the tasks, we deploy a float we constructed to complete vertical profiles of the area. The float operates through the use of a buoyancy engine powered by a linear actuator, which changes the volume of the float by moving a machined plug within a tube open to the water. This causes the float's density to change, letting it complete its vertical profiles without any outside assistance.

Computer Vision

Photomosaic

For the photomosaic, we manually take eight images, one of each grid rectangle. Using the opencv stitcher class, we then stitch the images together and output the new image to the screen.

Measure Wreck and Fish

These tasks both use the same general algorithm. After the pictures are taken, the user selects 4 points on the image. The first two points correspond to a known distance. For the fish, the distance from dorsal fin to tail is 15 cm. For the wreck, the side distance for one of the rectangles is 50 cm. We use these lengths and the pixel distance between the first two points to create a ratio of cm / pixel. Then, the pixel distance from the next two points is multiplied by this ratio to return the actual distance in centimeters between those two points.

Mapping the Wreck

First a reference image of the transect is taken, then the copilot clicks on the blank map to draw the lines of the wreck on the map. Finally, the copilot rotates the map to align it with the side of the pool.

Build vs Buy, New vs Used

The ROV uses a mix of custom built and COTS parts tailored for a low cost with high reliability and efficiency. COTS parts, while generally more expensive, also generally offer a higher degree of reliability, making them ideal for critical components such as the enclosures responsible for keeping the electronics dry. For components such as the ROV's frame, manufacturing them ourselves allows for the components to be better suited to our specific needs, all while at a lower price.

Being our second year competing with MATE, we had several major components that we could reuse. The ROV's manipulator, thrusters, main electronics enclosure, and control box, are all reused from last year. The ROV also has many new components, as we redesigned the frame and electronics to better suit this year's challenge and to take what we learned into fruition.

Teamwork

Project Management

Each member of the Robosharks has worked together in the past, so each of us has a good understanding of everyone else's skill sets. This allows us to structure our company based on who is best suited for the job at hand. With this, we are able to assign tasks tailored to each member's expertise. Most tasks, however, are more interdisciplinary and require the expertise of more than one member, so, more often than not, we have multiple members working on each task. This helps members to learn from each other and allows for better introduction and circulation of ideas.

Scheduling and Planning

We wanted to have as much participation from the members of our company as possible, so our meeting schedules were designed with accessibility in mind. We built our schedule around the days that could have the highest attendance, using data we gathered through surveys and observation.

We started with infrequent meetings during the fall and early winter, meeting once a week in order to train our new members and do early design work on the structure of the ROV.

	A	Task	Deadline	Criticality	Difficulty	Done?	G
2		order redundend electronics	immediate	HHH	L	☑	list together
3		design adjustable camera mount	docs submission	H	M	☑	
4		build camera mount	worlds	H	M	☑	
5		design float	docs submission	HHH	HH	☐	conceptual complete
6		build float	worlds	HHH	HH	☐	
7		make spec sheet	docs submission	HHH	M	☐	
8		voltage self-measurement	worlds	H	M	☐	designed
9		re-wrap tether	worlds	H	M	☐	
10		remake electronics tray	worlds	H	L	☐	
11		fix brownouts	worlds	HHH	HH	☐	
12		functional depth sensor	worlds	H	HH	☐	
13	NEED	Redo tech docs, spec sheet, SID, safety review	docs submission	HHH	HH	☐	
14		depth PID	docs submission	M	HH	☐	
15		functional IMU	docs submission	M	HH	☐	
16		orientation PID	docs submission	M	HHH	☐	
17		leak sensing	worlds	L	M	☐	
18		Vision + autonomous	docs submission	M	HHH	☐	
19		code refactor	worlds	M	HH	☐	
20	WANT	washer replacement (wider)	worlds	M	L	☐	

Figure 10: Prioritized todo list

Once the competition documentation had been released, we shifted to a more active meeting schedule with meetings three times a week from 4:00 - 5:00 held on Mondays, Wednesdays, and Thursdays to stay on top of the competition deadlines.

Most of our planning was built around an end date where we wanted to have a fully functional ROV, which left us with plenty of room to adapt and respond to issues and problems as they arose.

Communication

Our primary platform for communication and planning was Discord, where we created channels for different categories to expedite communication, and had space for people to discuss timelines and challenges as we worked. In addition, we also used email to send out important information to the company, since while Discord works well for discussion, it is not as effective for important company wide announcements.

Additionally, we utilized GitHub and GrabCAD for code and cad version control, respectively. These programs allowed for easier and more efficient collaboration between team members. Finally, we used Google Drive to create a company shared drive, which allowed us easy sharing of pdfs, spreadsheets, and text documents.

Safety

Operations

1. Check that enclosures are sealed and all plugs are closed.
2. Check that the strain relief is secure at both ends of the tether.
3. Check that all cables are clear of the motors.
4. Power on ROV and wait for signal beeps.
5. ROV is ready for launch.
6. Always walk at the poolside.
7. In event of an emergency leak, immediately power down ROV and pull it out of the water by the tether.

Construction

1. Always have teacher mentor present when operating power tools
2. Wear proper PPE (ear, eye, and hand protection) and closed toed shoes when operating power tools.
3. Turn ventilation on for power tools that require it.
4. Remove or secure loose clothing.
5. Never leave CNC or laser cutter unattended

Safety Features

Strain Relief

Our tether is looped around a set of cable thimbles attached to a U-bolt before going into the main body of the ROV. This ensures that there is no tension on the cable penetrators and allows us to pull the ROV out by the tether if the need arises.

Propeller Guards

Our propeller guards are 3D printed guards designed for use with the T200 thrusters we're using. They are sturdy enough to resist breaking during use and are rated at IP-20 (fingerproof).

Fuse

The ROV uses a 25 amp fuse, located within 30 cm of the power supply for overcurrent protection.

Critical Analysis

Testing and troubleshooting

Our company performs many tests of the ROV to determine functionality. Frequent tests are leak tests, buoyancy tests, and software tests.

To ensure that the electronics and camera enclosures are sealed, we submerged each enclosure underwater for an extended period of time. This test allows us to detect if any cable penetrators are improperly sealed, or a leak occurs anywhere else in the enclosure. At the pool, we need to get the ROV as close to neutral buoyancy as possible, so we gradually add and remove buoyancy foam until the ROV is stable. Any time a change is made to the ROV, we reevaluate the ROV's buoyancy to see if any changes are necessary. There are many different components of software that go into the final code; we break down the code into individual sections, such as cameras, controller, and movement, and test each individually to make sure that section works before adding them to the final program, allowing us to pinpoint errors and bugs in the code.

Acknowledgements

The Robosharks would like to thank the following people and organizations:

- Jim and Dede Bartlett Foundation and Ball Corporation for financial support.
- Riana Sartori and Teledyne FLIR for our cameras.
- Boulder Parks and Rec and the Rao Family for letting us use their pools.
- Our mentors and sponsors Mr. Zahner and Ms. Zimmerman for their time and guidance.
- Last but not least, MATE for the amazing educational opportunity.

References

- Blue Robotics for T200 datasheets.
- McMaster for CAD of components.
- Stackoverflow for programming help.

Appendices

Appendix A: ROV SID

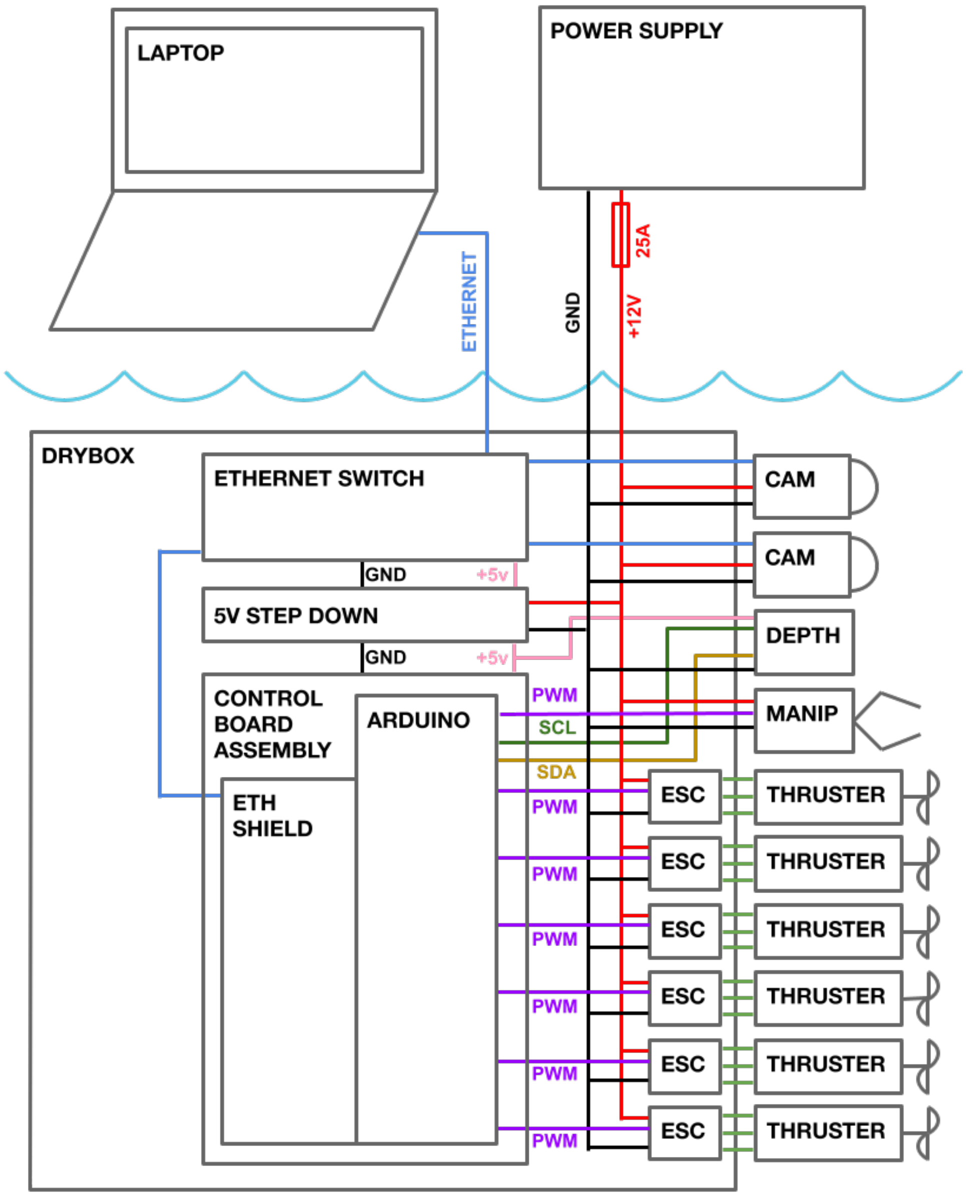


Figure 11: ROV Electronics SID

Appendix B: Float SID

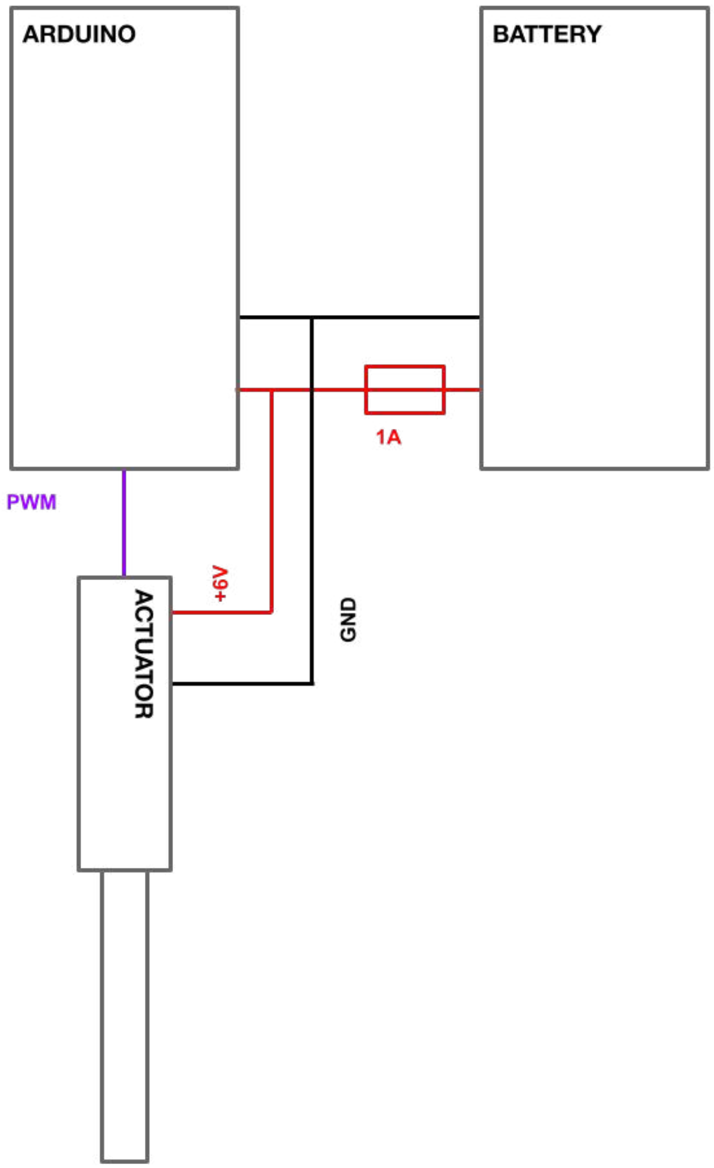


Figure 12: Float SID

Appendix C: Job Site Safety Analysis

Job Task	Potential Hazards	Control Measures
Entering/exiting the pool area	Slipping on pool deck	Be aware of surroundings Walk, don't run
	Dropping equipment	Secure all equipment in appropriate containers
	Lifting injuries	Ask for help lifting heavy objects
System setup	Getting water on equipment	Don't place equipment on floor Keep cables away from water
	Tripping over wires	Pay attention to where the tether is Keep wires flat on the ground
	Environmental factors	Do not operate ROV in electrical storms
Power-up checks	Voltage spikes	Turn off power supply before plugging in ROV
	Electric shocks	Check for loose wires Keep cables away from water
Poolside operations	Falling in pool	Do not reach far over edge of pool to retrieve props Have a lifeguard present
	Injury from ROV	Wait until all ROV motors have stopped before reaching into water
Clean-up	Falling in pool	Do not reach too far out into pool to retrieve ROV
	Injury from lifting ROV	Ask for help lifting heavy objects

Figure 13: Job Site Safety Analysis

Appendix D: Bill of Materials

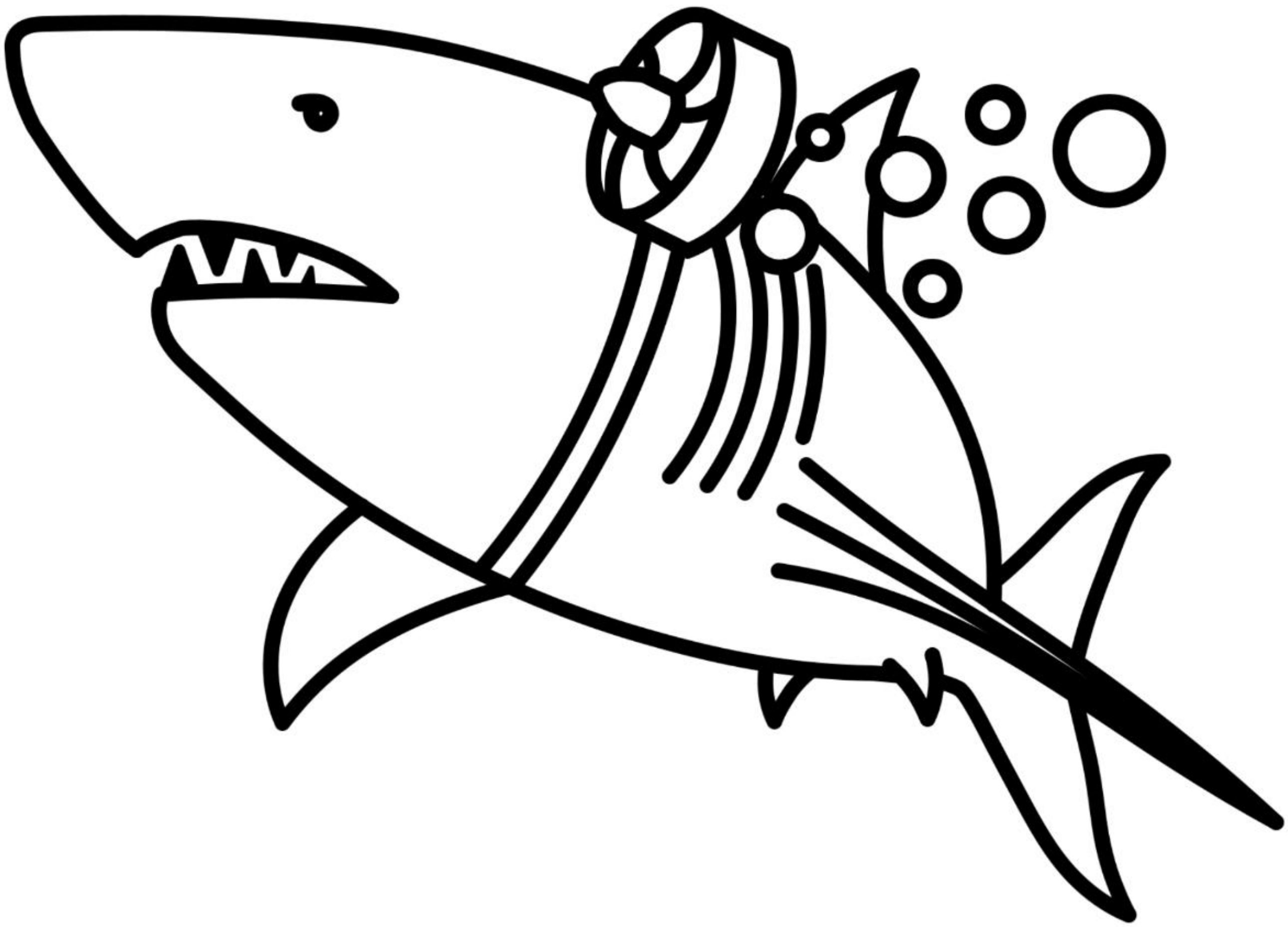
Type	Group	Item	Price	#	Cost
Purchased	Solderless breadboard	Solderless breadboard	$5.00	1	$5.00
Purchased	Soldered breadboard	Soldered breadboard	$5.00	1	$5.00
Purchased	Voltage/Current sensor	Voltage/Current sensor	$20.00	1	$20.00
Purchased	Arduino ethernet shield	Arduino ethernet shield	$27.00	1	$27.00
Purchased	Jumper Wires	Jumper Wires	$25.00	1	$25.00
Purchased	Headers	Headers	$1.00	2	$2.00
Purchased	Arduino MKR Zero	Arduino MKR Zero	$27.00	1	$27.00
Purchased	penetrator	penetrator	$246.00	1	$246.00
Purchased	M10 penetrator blank	M10 penetrator blank	$6.00	3	$18.00
Purchased	2" series enclosure	2" series enclosure	$108.00	2	$216.00
Purchased	electronics	various electronics	$728.00	1	$978.48
Purchased	Float	float parts	$155.92	1	$155.92
Purchased		Thimble	$3.00	3	$9.00
Purchased	Strain relief	u-bolt	$6.00	1	$6.00
Purchased	Tools	1/4-20 stainless nut	$8.00	1	$8.00
Purchased	tools	carbide drill bit	$12.00	1	$12.00
Purchased	pvc	2-1 pvc reducer	$3.85	2	$7.70
Purchased	pvc	1 in pvc plug	$1.00	1	$1.00
Purchased	tools	Replacement soldering iron ti	$10.00	1	$10.00
Purchased	pressure relief valves	pressure relief valve	$30.00	1	$30.00
Purchased	frame	T-Slotted Framing Angle brack	$5.75	8	$46.00
Purchased	frame	Unthreaded Spacer Stock	$11.54	4	$46.16
Purchased	hardware	hardware	$171.73	1	171.73
Purchased	frame	20 mm t-slot framing	$10.84	4	$43.36
Purchased	tether	More penetrators (TBD)	$50.00	1	$50.00
Purchased	tether	More penetrator blanks	$6.00	5	$30.00
Purchased	tools	Updated penetrator wrench	$16.00	1	$16.00
Purchased	frame	New back cap	$48.00	1	$48.00
Purchased	tape	Cable Repair Tape	$8.00	1	$8.00
Purchased	grease	Silicone Grease	$3.00	1	$3.00
Re-Used	Manipulator	Newton Gripper	$590.00	1	$590.00
Re-Used	Thrusters	T200 Thruster	$236.00	6	$1,416.00
Re-Used	electronics	Blue Robotics Basic ESCs	$36.00	6	$216.00
Re-Used	frame	4 inch tube	$90.00	1	$90.00
Re-Used	frame	O-ring flange	$29.00	2	$58.00
Re-Used		Waterproof case	$150.00	1	$150.00
Re-Used		10 inch monitors	$75.00	2	$150.00
Re-Used	control box	Dell Latitude E7470	$370	1	$370
Donation	Cameras	FLIR Blackfly cameras	$337	2	$674
Overall Total					$5,985.35

Figure 14: Bill of Materials

Appendix E: Project Costing and Budgeting

School Name	Boulder High School			**Reporting Period**	
Sponsors	Mr Zahner	Ms Zimmerman		From	10/1/2021
				To	5/14/2022
Income					
Source					
Jim and Dede Bartlett Foundation					
State payments for passing CSWA					
Expenses					
Category	**Description/examples**	**Projected cost**	**Budgeted Value**		
Electronics	arduino, sensors, etc.	$1,000	$1,000		
Hardware	nuts, bolts, polycarb, etc	$1,000	$1,000		
Props	MATE competition props	$400	$400		
Food	snacks, pizza, for meetings	$600	$600		
		Total expenses:	$3,000		

Figure 15: Project Costing and Budgeting



"Why do we have tech docs without having a tech port?"
- Mikael Steinman