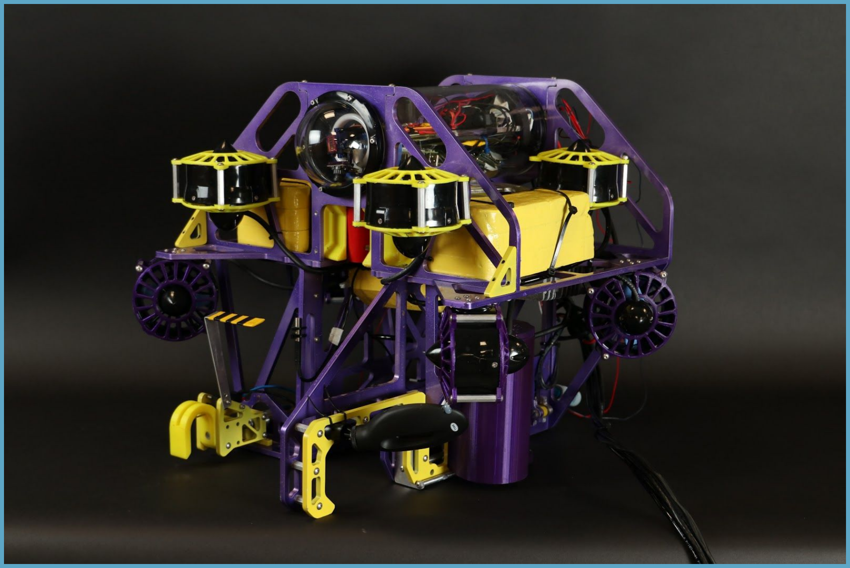
CWRUbotix

2019 Technical Documentation

Innovations for Inshore: ROV Operations in Rivers, Lakes, and Dam

Case Western Reserve University
Cleveland, OH



The Wobbegong

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Introduction

Abstract

CWRUbotix is an entirely student-run company from Case Western Reserve University. For 2019, the CWRUbotix executive board and technical leadership decided to expand its annual competition roster to include the MATE ROV competition alongside the NASA Robotic Mining Competition and National Robotics Challenge.

As a first-year company, we dove head-first into developing a vehicle to meet the requirements of Eastman and the MATE ROV Competition. We believe we have produced a competitive system with both a strong base-line performance and some novel capabilities that simplify operation, reduce costs, and enhance reliability.

In this document, we will discuss the technical capabilities of our final system, justify key technical and system-level decisions made throughout our development process, and provide a detailed overview of our project management and technical development strategy.

Fig. 1: The team.

Safety

Safety Philosophy

The safety of all of the members of our team, as well as everyone in our surrounding environment is of utmost importance to us at all times. We subscribe to the belief that all accidents are preventable with the proper planning, which gets reflected in our thoughtful and intentional design, construction, and operation, ensuring the safety of all involved.

Safety Standards and Features

CWRUbotix operates from a small lab space located within Sears' think[box], Case Western's 50,000 square-foot open-access innovation center and makerspace. In all of our work in think[box], as well as elsewhere during testing, we ensure that all company members are following the safety rules set in place by think[box] as well as additional ones specific to our company. When using anything in the machine shop—including the Waterjet Cutter, saws, mills, and lathes—members must be in proper Personal Protective Equipment—short sleeves, long pants, closed toe shoes, and safety glasses.

When operating the ROV, commands are clearly communicated between the drive team and those managing the tether, launching the ROV, recovering objects in the water, or otherwise in contact with the vehicle. Commands are primarily communicated by the driver to the rest of the operations team and action is taken upon an affirmative response from team members. However, when the operating team has hands on the robot, those handling the robot or recovering mission props give commands for pneumatic actuation. While standard loading procedure for the vehicle ensures a safe distance from powered systems is maintained at all times, this avoids the potential for serious injury due to actuation.

To ease this communication, we maintain clear standards between the poolside crew and remote operators through a standard set of keywords so that everyone can know what to expect or what actions must be taken. We have two sets of keywords, those communicated by the operator to the poolside crew to alert them of action being taken - Arm, Engage, and Charge - as well as those communicated by either party to the other when something has gone wrong, an object has been recovered, or there must otherwise be contact with the vehicle - Disarm, Disengage, and Dump.

In order to allow for fast response time to the above commands, we have included an emergency stop button on the side of our controller station, referred to hereafter as the E-Stop. In the event that there is any verbal command to stop from any members in the pool, poolside, or at the controller station, this gives the fastest possible response time by fully cutting off power to the system. Additionally, if any unexpected behavior is observed this allows for expedient response time in stopping it and allowing for the system to be recovered and inspected for damage.

The pneumatic system also has an important safety feature similar to the E-Stop, the dump valve. This valve allows for immediate release of pressure in the lines down to the ROV.

The E-Stop and dump valve together are important parts of our operation and testing procedure. Before any individual in the water with the ROV or poolside comes into nonstandard contact with the vehicle, communication is made between the individual and the controller and the robot is pneumatically and electrically de-energized before contact may occur.

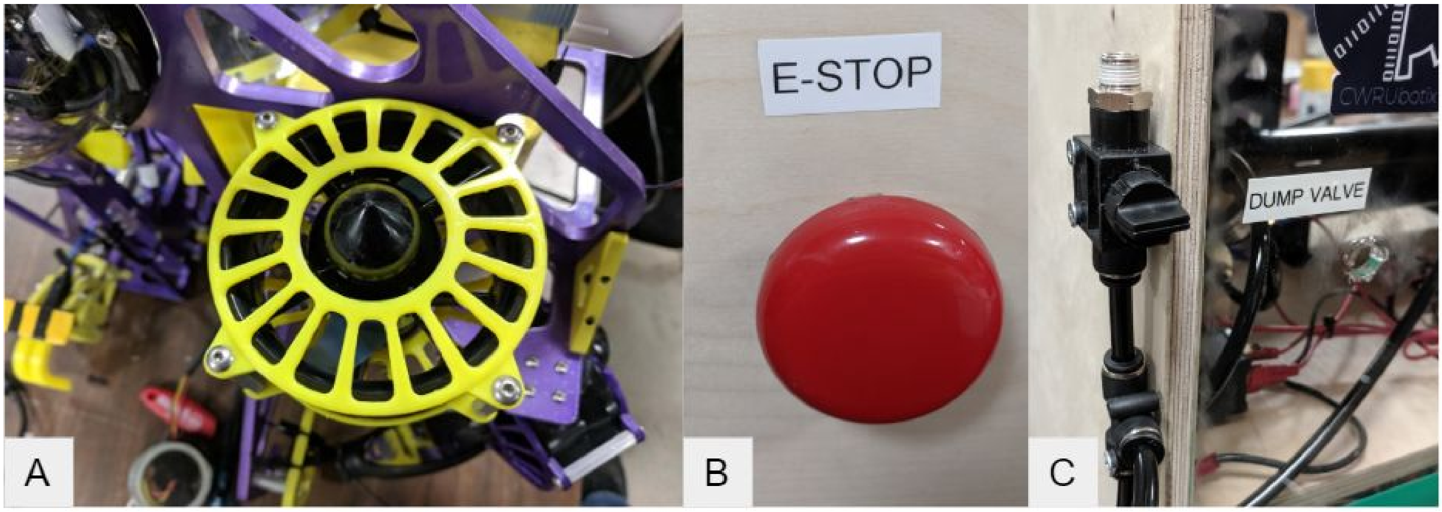


Fig. 2: Safety features: Thrusters are shrouded to keep fingers and debris out (A). Emergency stop to cut power to the robot (B), pneumatic dump valve to relieve tank pressure (C).

A variety of safety features have been integrated into the mechanical and control designs of the system. All of the moving systems besides the pneumatic actuators as described above are properly shrouded to protect team members in the case adjacent contact must occur. For example, the thrusters each have a requirement compliant shroud as shown above.

Additional safety features are directly integrated into the mechanical construction in order to prevent possible incidents in handling. First, to prevent scratches and snags, the corners of the metal plates are all filleted and the edges chamfered. With this, it is safe to grab the ROV anywhere when it is not armed. Though it can be grabbed anywhere, there are also handles integrated into the upper plates of the vehicle that serve as easy recovery points for the poolside crew as well as for general carrying convenience. To prevent snagging and injury with the tether, we have also chosen to sleeve the entire length in order to give an even constant surface that is easy to handle and will not get caught which could potentially cause trip hazards. Finally in the event that the tether does become snagged, we have integrated strain relief into both the controller and robot ends of the tether. The strain relief is accomplished by wrapping the tether around a 3D-printed loop and securely fastening that to the robot and control station while leaving slack between that and the electrical connections. In the event that the robot must be manually recovered, this also allows us to pull it in by the tether without straining or compromising the electrical connections.

Project Management

Project Management Methodology

CWRUbotix employs a stage-gate systems engineering approach to plan, document, and support the development of its robots. By employing this methodology throughout the project lifecycle, we ensure that our system meets all customer and derived requirements, stays on track for critical deadlines, and undergoes detailed external design reviews at several phases throughout the system's development. Key project-management tools used to accomplish this are discussed below.

Org-Chart

To aid in the process of structuring our company, we created an org-chart to break down roles and reporting structure. The team lead serves as the head project manager and supports technical development at a system level. The mechanical, fabrication, software, and hardware leads in turn manage the members, workload, and technical development for their respective sub-system.

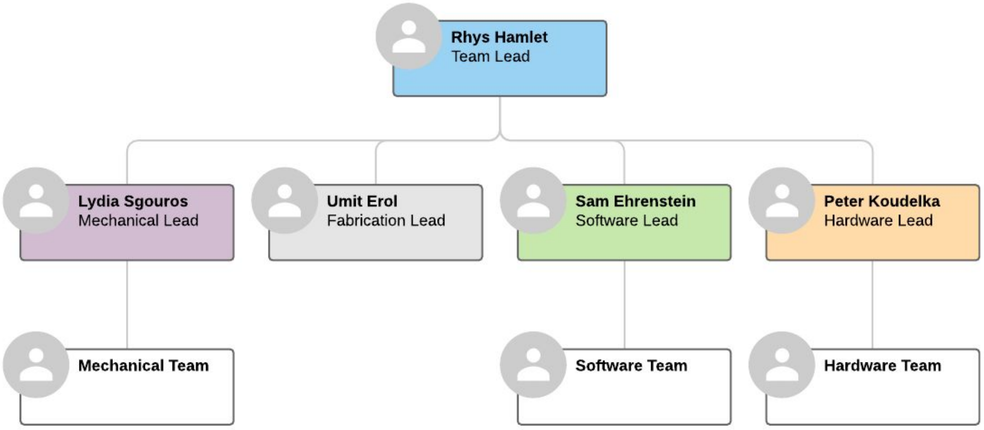


Fig. 3: Company Org. Chart

Project Phases and Design Reviews

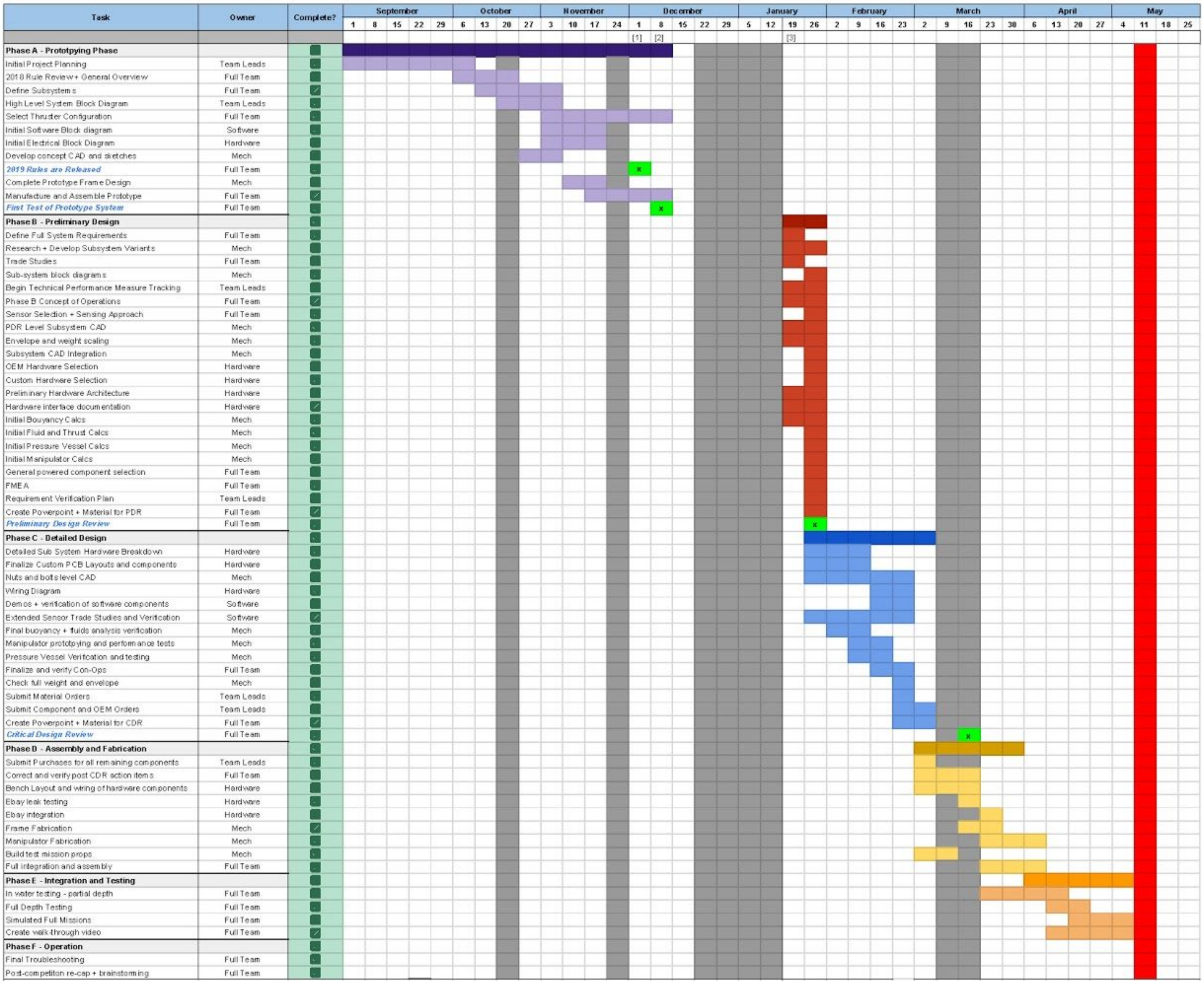
We split our project into six phases in order to set clear expectations for what would happen during each portion of our development timeline, break-down how complexity should evolve during the design process, and set deadlines for key milestones in the project.

Phase	**Name**	**Key Objectives**	**Method of Review**
A	*Prototyping Phase*	Create subsystems, structure team, define system-level architecture, design and construct a prototype system for in pool testing.	Successful launch of prototype system and internal review
B	*Preliminary Design*	Define all requirements and concept of operations, perform trade-studies, make initial calculations CAD, etc. for all subsystems.	Preliminary Design Review
C	*Detailed Design*	Complete design work for all systems at a final level of detail. All subsystems should have working proof of concepts and be ready for final implementation.	Critical Design Review
D	*Assembly and Fabrication*	Complete the assembly and fabrication of the system.	Release for Manufacturing Reviews
E	*Integration and Testing*	Test and evaluate the performance of the system.	Completing testing objectives
F	*Operation*	Successfully operate the system to meet the requirements of the product demonstration.	Performance during product demonstration

Fig. 4: Breakdown of Project Phases

Timeline Management

In order to structure our timeline, create internal deadlines, and track our day-to-day progress during development, we created a Gantt chart *(Fig. 5)*. Every item has a completion check box and primary owner in order to define specific sub-team tasks at all points during development. The timeline is organized per the project phases outlined above.



Task	Owner
Phase A - Prototpying Phase	
Initial Project Planning	Team Leads
2018 Rule Review + General Overview	Full Team
Define Subsystems	Full Team
High Level System Block Diagram	Team Leads
Select Thruster Configuration	Full Team
Initial Software Block diagram	Software
Initial Electrical Block Diagram	Hardware
Develop concept CAD and sketches	Mech
2019 Rules are Released	Full Team
Complete Prototype Frame Design	Mech
Manufacture and Assemble Prototype	Full Team
First Test of Prototype System	Full Team
Phase B - Preliminary Design	
Define Full System Requirements	Full Team
Research + Develop Subsystem Variants	Mech
Trade Studies	Full Team
Sub-system block diagrams	Mech
Begin Technical Performance Measure Tracking	Team Leads
Phase B Concept of Operations	Full Team
Sensor Selection + Sensing Approach	Full Team
PDR Level Subsystem CAD	Mech
Envelope and weight scaling	Mech
Subsystem CAD Integration	Mech
OEM Hardware Selection	Hardware
Custom Hardware Selection	Hardware
Preliminary Hardware Architecture	Hardware
Hardware interface documentation	Hardware
Initial Bouyancy Calcs	Mech
Initial Fluid and Thrust Calcs	Mech
Initial Pressure Vessel Calcs	Mech
Initial Manipulator Calcs	Mech
General powered component selection	Full Team
FMEA	Full Team
Requirement Verification Plan	Team Leads
Create Powerpoint + Material for PDR	Full Team
Preliminary Design Review	Full Team
Phase C - Detailed Design	
Detailed Sub System Hardware Breakdown	Hardware
Finalize Custom PCB Layouts and components	Hardware
Nuts and bolts level CAD	Mech
Wiring Diagram	Hardware
Demos + verification of software components	Software
Extended Sensor Trade Studies and Verification	Software
Final buoyancy + fluids analysis verification	Mech
Manipulator prototpying and performance tests	Mech
Pressure Vessel Verification and testing	Mech
Finalize and verify Con-Ops	Full Team
Check full weight and envelope	Mech
Submit Material Orders	Team Leads
Submit Component and OEM Orders	Team Leads
Create Powerpoint + Material for CDR	Full Team
Critical Design Review	Full Team
Phase D - Assembly and Fabrication	
Submit Purchases for all remaining components	Team Leads
Correct and verify post CDR action items	Full Team
Bench Layout and wiring of hardware components	Hardware
Ebay leak testing	Hardware
Ebay integration	Hardware
Frame Fabrication	Mech
Manipulator Fabrication	Mech
Build test mission props	Mech
Full integration and assembly	Full Team
Phase E - Integration and Testing	
In water testing - partial depth	Full Team
Full Depth Testing	Full Team
Simulated Full Missions	Full Team
Create walk-through video	Full Team
Phase F - Operation	
Final Troubleshooting	Full Team
Post-competiton re-cap + brainstorming	Full Team

Fig. 5: Gantt Chart

System-Level Design

Concept of Operations

We used a dive plan and a standard operating procedure (SOP) to document and implement our concept of operations. The dive plan specifies the order in which tasks are performed and the intervals where the vehicle returns to the surface for load/unload. The SOP is a detailed overview of operating procedure followed by the product demonstration operations team.

Dive #	Dropped	Recovered	Sub Tasks
1	Trout, Reef Ball	Old Trash Rack	Benthic Species, PH and Temp Sampling
2	New trash rack, grout, cannon shell markers	Tire	Mini ROV, Line Follow
3		Cannon	

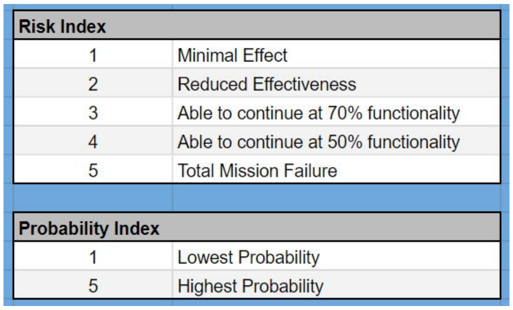
Fig. 6: Summary of Dive Plan

Failure Modes Effects Analysis

To identify potential areas of high-risk failure, we performed a failure modes effects analysis (FMEA). For each potential failure a probability of occurrence and resulting risk to function of the system was assigned. From these numbers a risk priority number (RPN) was calculated as the product of these values. For each risk, a mitigation approach was then recommended and particularly high RPN failures were given special attention. Somewhat predictably, water ingress failures resulted in the highest *RPN* values by a large margin. Our full FMEA sheet, as well as an index for risk and probability values are shown below:

#	Failure	Probability	Risk	RPN	Mitigation
1	Water ingress into ebay	3	5	15	
2	Thuster Failure (Jamming/Entanglement)	1	4	4	Shrouds
3	Thruster Failure (Water Ingress)	1	5	5	Validated Purchased Part
4	Severe Thruster Misalignment	1	4	4	Rigid mounting and frame design
5	Uncorrectable Rollover	1	5	5	6 DOF Capability and Bouyancy Bias
6	Tether entanglement	3	3	9	TMS / Manual TM proccedure and practice
7	Tether termination strain	2	2	4	Strain relief at terminations
8	Tether breakage	1	5	5	Thether sleeving, adaquite tensile strength
9	Water ingress through tether	2	5	10	Validated Purchased Part, Expanding Fibers
10	Pneumatic line failure	2	3	6	Strain relief, sleeving, and bundle float
11	Excessive tether drag	3	2	6	Compensated tether bouyancy
12	Frame bending	1	2	2	FEA analysis of frame
13	Powered component failure (water ingress)	4	4	16	Designed enclosures with rated o-rings
14	Powered component failure (Jamming/Entaglement)	3	2	6	Compliance, Jam clearing proceedures
15	Powered component failure (internal damage/stall)	1	4	4	Compliance, Stall detection
16	Pneumatic line water ingress	3	1	3	Safety factor on flowrate, rated fittings
17	Continous camera obstruction	2	3	6	Reorientation proceedure, design for prop orientations
18	Camera Failure (Electrical)	1	5	5	Pre-operation tests, spare parts
19	Camera Failure (Insufficient light)	3	3	9	Onboard lights, operating proceedure
20	Sensor Failure (Physical/Electrical)	2	3	6	Protective probe structure, spare parts, validated OEM
21	Sensor Failure (Bad Calibration/Outliers)	4	2	8	Outlier rejection, calibration proceedures
22	Loss of bouyancy	1	4	4	Leak-proof bouyancy method, robust rentention
23	Loss of ballast	1	3	3	Robust ballast retention and containment
24	Bad buoyancy ballast balance	2	2	4	Active ballast system for each payload config
25	Unstable active roll/yaw stabilization	2	2	4	Tuning, option to disable active stabalization
26	Unstable active depth hold	2	2	4	Tuning, option to disable depth hold

Fig. 7: FMEA Sheet (above) and Risk and Probability Index (below)

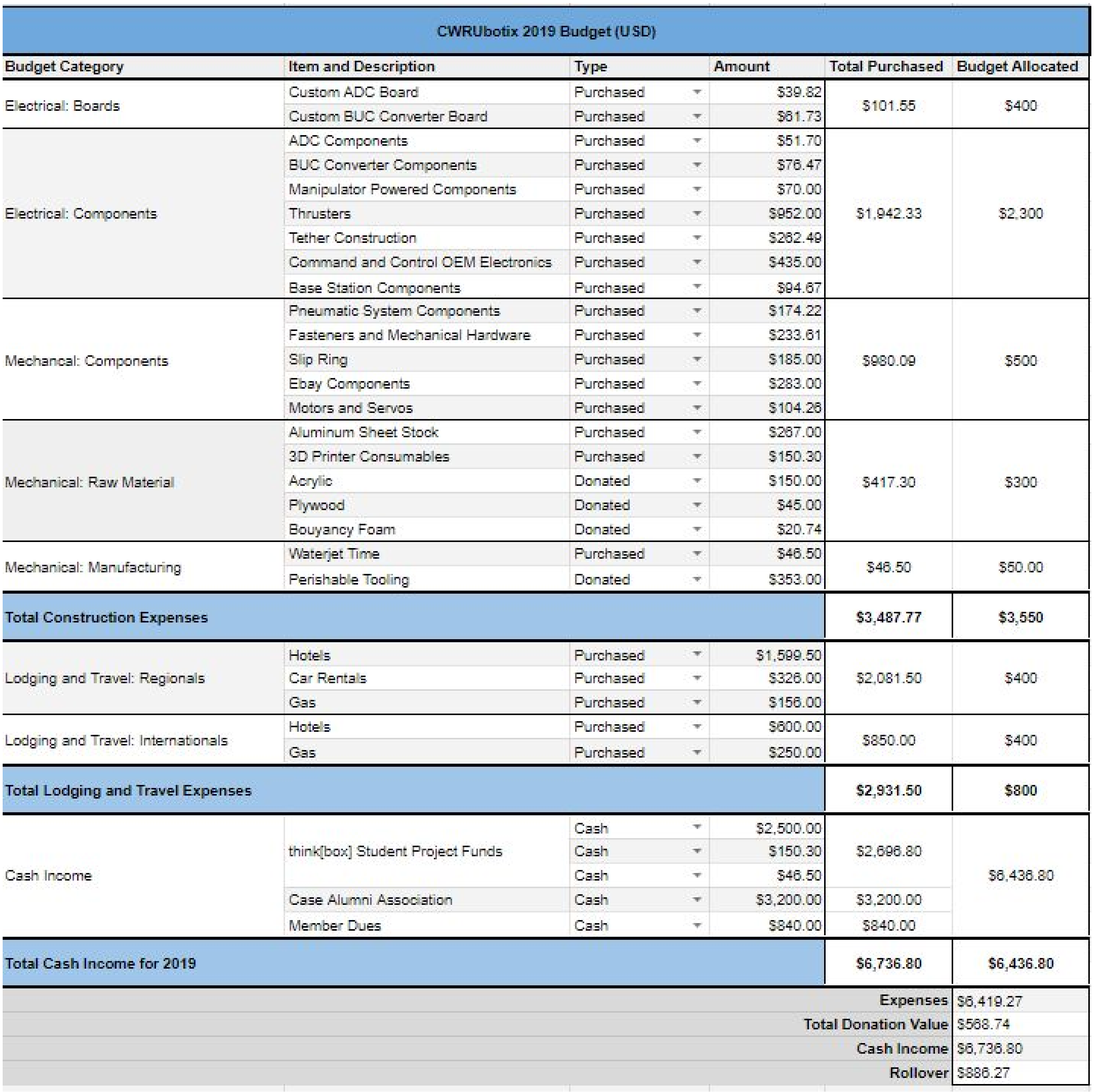


Risk Index	
1	Minimal Effect
2	Reduced Effectiveness
3	Able to continue at 70% functionality
4	Able to continue at 50% functionality
5	Total Mission Failure

Probability Index	
1	Lowest Probability
5	Highest Probability

Project Costing and Budget

The following table illustrates the actual and allocated cost for ROV Construction, Lodging and Travel, the value of all donations received, cash income received for 2019 for the project, and final totals.



CWRUbotix 2019 Budget (USD)

Budget Category	Item and Description	Type	Amount	Total Purchased	Budget Allocated
Electrical: Boards	Custom ADC Board	Purchased	$39.82	$101.55	$400
	Custom BUC Converter Board	Purchased	$61.73		
Electrical: Components	ADC Components	Purchased	$51.70	$1,942.33	$2,300
	BUC Converter Components	Purchased	$76.47		
	Manipulator Powered Components	Purchased	$70.00		
	Thrusters	Purchased	$952.00		
	Tether Construction	Purchased	$262.49		
	Command and Control OEM Electronics	Purchased	$435.00		
	Base Station Components	Purchased	$94.67		
Mechancal: Components	Pneumatic System Components	Purchased	$174.22	$980.09	$500
	Fasteners and Mechanical Hardware	Purchased	$233.61		
	Slip Ring	Purchased	$185.00		
	Ebay Components	Purchased	$283.00		
	Motors and Servos	Purchased	$104.26		
Mechanical: Raw Material	Aluminum Sheet Stock	Purchased	$267.00	$417.30	$300
	3D Printer Consumables	Purchased	$150.30		
	Acrylic	Donated	$150.00		
	Plywood	Donated	$45.00		
	Bouyancy Foam	Donated	$20.74		
Mechanical: Manufacturing	Waterjet Time	Purchased	$46.50	$46.50	$50.00
	Perishable Tooling	Donated	$353.00		
Total Construction Expenses				**$3,487.77**	**$3,550**
Lodging and Travel: Regionals	Hotels	Purchased	$1,599.50	$2,081.50	$400
	Car Rentals	Purchased	$326.00		
	Gas	Purchased	$156.00		
Lodging and Travel: Internationals	Hotels	Purchased	$600.00	$850.00	$400
	Gas	Purchased	$250.00		
Total Lodging and Travel Expenses				**$2,931.50**	**$800**
Cash Income	think[box] Student Project Funds	Cash	$2,500.00	$2,696.80	$6,436.80
		Cash	$150.30		
		Cash	$46.50		
	Case Alumni Association	Cash	$3,200.00	$3,200.00	
	Member Dues	Cash	$840.00	$840.00	
Total Cash Income for 2019				**$6,736.80**	**$6,436.80**
				Expenses	$6,419.27
				Total Donation Value	$568.74
				Cash Income	$6,736.80
				Rollover	$886.27

Fig. 8: CWRUbotix 2019 budget

Mechanical Design Rationale

Frame

The frame was manufactured from ¼” (6.35mm) 6061 Aluminum plates. In choosing material and manufacturing method, initial trade studies considered various materials—polymers, Aluminum, and Stainless Steel—as well as a variety of construction methods—plate, tube, and rod structures. *Fig 9* below shows charts from our initial consideration of polymers. We first identified totally and partially non-hygroscopic options and then compared them in cost, strength, and weight.

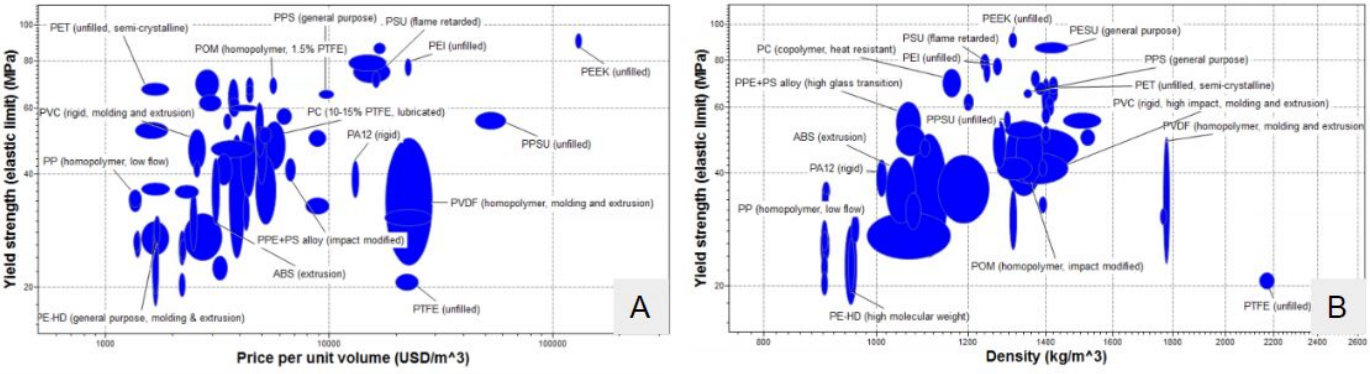


Fig. 9: Polymer materials considered for the frame compared in cost and strength (A) and in strength and density (B) using CES EduPack.

With this, we chose a machined PVC frame as the best polymer frame option given its desirable characteristics, wide availability, machinability, and common use in prior art. A simple ROV prototype was built early in our development to evaluate preliminary designs and gain hands-on experience with ROVs to aid our rookie company. This prototype was constructed out of polymer plates with few metal components. However, the prototype proved to be difficult to operate due to the large surface area of the plates required to keep the structure rigid. We therefore decided against a polymer-only frame, opting to keep the structure more stiff with minimal material and resultant flow obstruction.

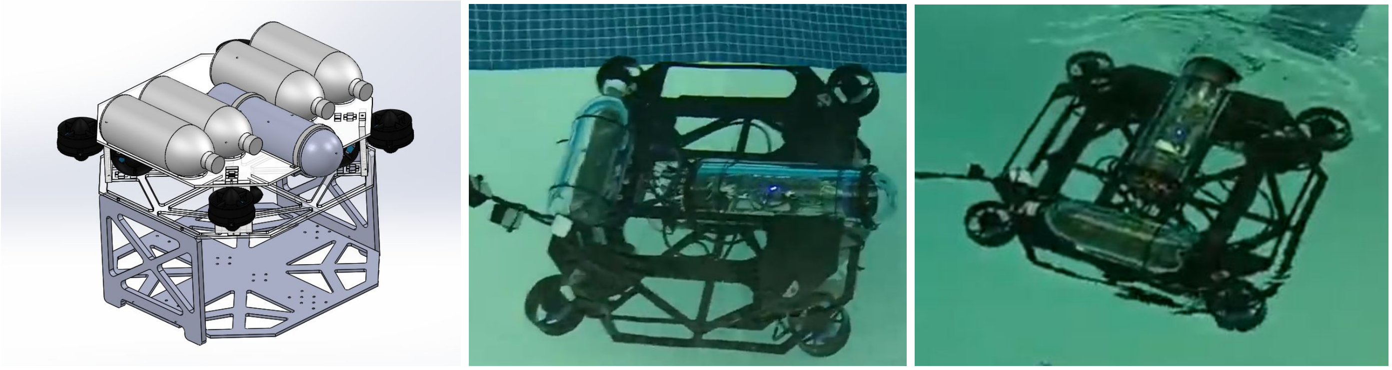


Fig. 10: Initial polymer ROV prototype allowed testing buoyancy and maneuverability, as well as basic software and hardware features.

A polymer-metal hybrid frame similar to the prototype was considered along with the following options: welded stainless steel rod, machined aluminum plate, and bent sheet metal. Fig. 11 below shows our final Pugh chart for the frame material and fabrication.

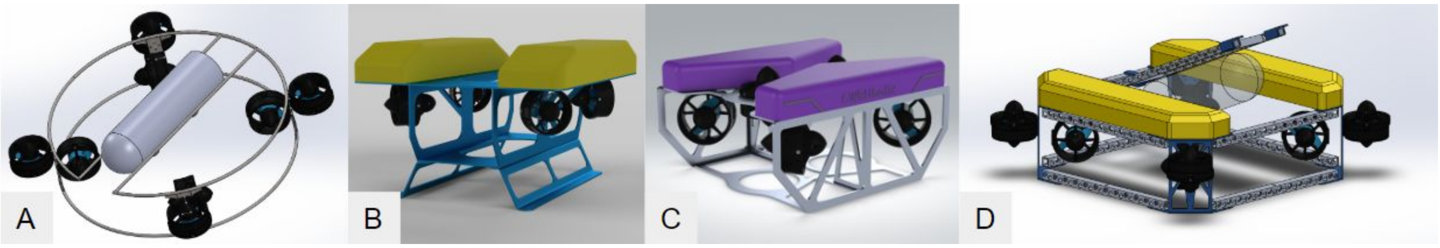


Fig. 11: Various frame concepts considered.

Ultimately, a machined aluminum frame was chosen. Although the aluminum and polymer/metal hybrid frame options scored very similarly in our final comparison, the aluminum frame has advantages not fully reflected on the Pugh chart: primarily, using a single material (¼” - 6.35 mm 6061-T6 Aluminum sheets) for the frame and load bearing components allowed us to standardize our fasteners as ½” (12.7

mm) #8-32 button head cap screws, with minimal non-standard sized exceptions. Second, by using a single material we were able to standardize our manufacturing process and did not have to change tooling and cutting conditions for different materials.

Characteristic	**Weight**	Stainless steel welded rod	Aluminum plate	Polymer/metal hybrid	Sheet metal
Weight	1	3	3	3	5
Manufacturability	0.4	4	3	3	2
Modularity	0.8	2	4	4	3
Complexity	0.6	5	4	4	3
Drag Force	0.1	3	3	2	3
Wire Routing	0.5	3	5	5	4
Expansion	0.7	2	4	4	3
Score:		**12.4**	**15.4**	**15.3**	**14.4**
1 - Worst		3	3	3	5
		1.6	1.2	1.2	0.8
		1.6	3.2	3.2	2.4
5 - Best		3	2.4	2.4	1.8
		0.3	0.3	0.2	0.3
		1.5	2.5	2.5	2
		1.4	2.8	2.8	2.1

Fig. 12: Final Pugh chart for frame construction.

The frame was designed around all of the mission tools using a highly integrated approach. Wherever possible, members of the frame also serve as structural members of the mission tooling.

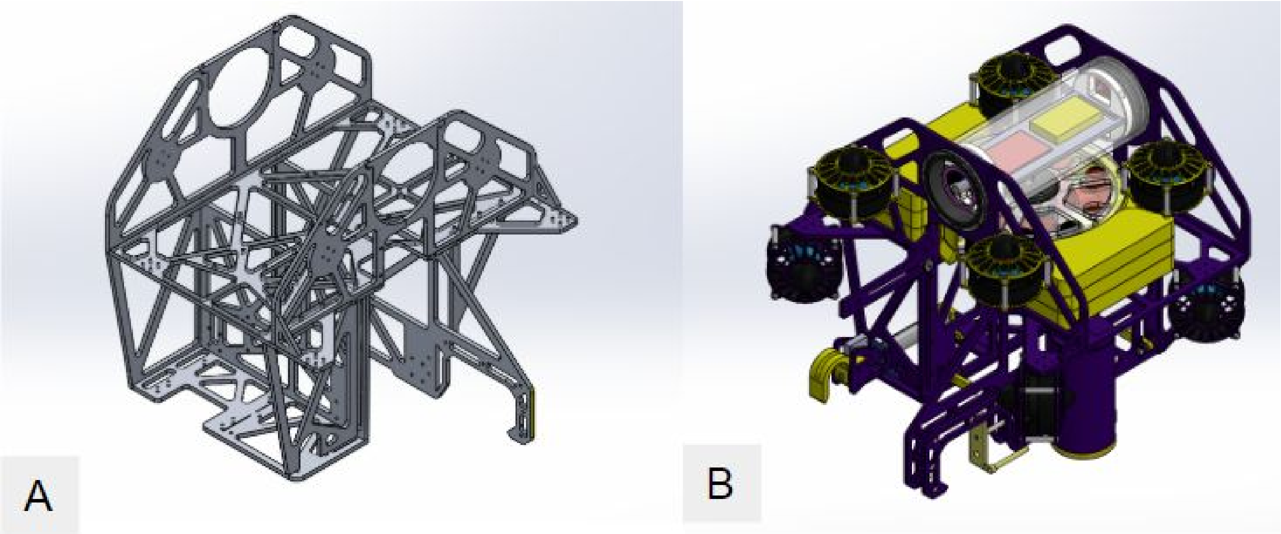


Fig. 13: Final frame CAD (A) and complete assembly CAD (B).

The frame parts were CNC-machined in house. Most of the frame parts required post-machining work such as tapped holes on the sides and back-side features, which were machined using manual mills. Several of the simpler parts were also fully machined manually in order to simplify CNC setups. All parts were deburred for safe handling, and then powder coated for durability and high visibility for operations, safety, and aesthetics.

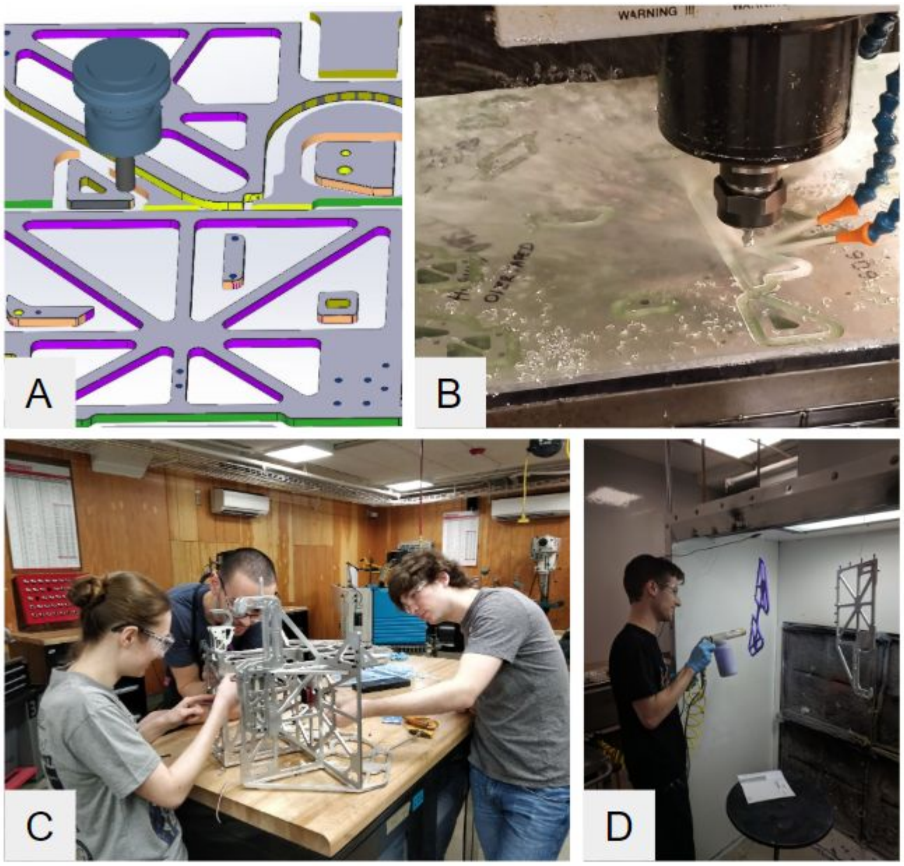


Fig. 14: Frame manufacturing process: CAM and programming(A); machining frame parts out of aluminum plate (B); post machining and dry assembly (C); powder coating before final assembly (D).

Electronics Bay (E-Bay)

To house our electronics, we decided to use parts from BlueRobotics's 4" Enclosure Series including a tube, dome, 18-hole end plate, and penetrators for that plate. We decided to purchase these parts for several reasons. First, with our aforementioned prototype system, one of our main goals was to make something that we could get in the water quickly in order to allow the software team to begin testing and to give a test platform for other mechanical systems. As a rookie team, we were concerned about our ability to design and manufacture a fully watertight enclosure in a time efficient and cost effective manner. Additionally, by taking this action, we helped to mitigate our highest rated risk, water ingress (see *Fig 7*).

Buoyancy

Our buoyancy is constructed from standard pink closed-cell Extruded Polystyrene Rigid insulation Foam sheet. We performed initial calculations regarding buoyancy volume in SOLIDWORKS using mass and volume estimates of all of the components. During testing we then used pool noodles and other flotation to approximate that weight and give us the freedom to decide whether we wanted the system to be slightly positively buoyant, slightly negative, or neutral. We ultimately decided that being slightly positive would be best for control and autonomy. Finally, we took a water weight of the vehicle and used this to form our final buoyancy, which was designed in SOLIDWORKS to attain the proper volume. This model was then sliced and resultant dxfs were used to cut the shapes out of the foam with our CNC Shopbot Router. The 2D shapes were then adhered together and sanded to create evenly sloped sides. The insulation foam is closed-cell and would work at depth but to further protect it we took a few additional steps following a successful test of the buoyancy. We painted the foam blocks in epoxy and finally spray painted it all yellow, adding to the safety and visibility of the system.

Mission Tools

In the initial planning and design stages, we considered a variety of complex manipulators like the one shown in *Fig. 15A* below that could accomplish many of the tasks on its own, or hold some sort of additional tool to accomplish the task.

Ultimately, we decided that the complexity of this sort of manipulator was unnecessary given the tasks required by Eastman and MATE. Everything that we would use the tool for on its own was a horizontal bar that could be held by a simple hook or rod and for the items that would require an extra tool, it made more sense to separate that task to its own simpler, dedicated manipulator. With this, SmartHook was born. SmartHook performs the same function as a simple hook but provides additional driver ease in that picking up objects only requires the driver to get above them with no hooking action required. Similarly, dropping off an object only requires them to get in the appropriate area before the hook is disengaged.

In simplification of the actuator design, we tried to minimize the number of actuated components as much as possible. We opted to use separate motors or servos for the T-dropper and winch but for everything else we used two pneumatic lines. This allows us to also keep the pneumatic controls fully on the surface with two lines going down in the tether. In normal operation, the two lines go to the SmartHook and SmartHook Jumbo, which is also connected to the drop box to further simplify operation. In cannon lift configuration, these two lines are rerouted to the two lift bag systems and no further changes in actuation or additional actuators are required.

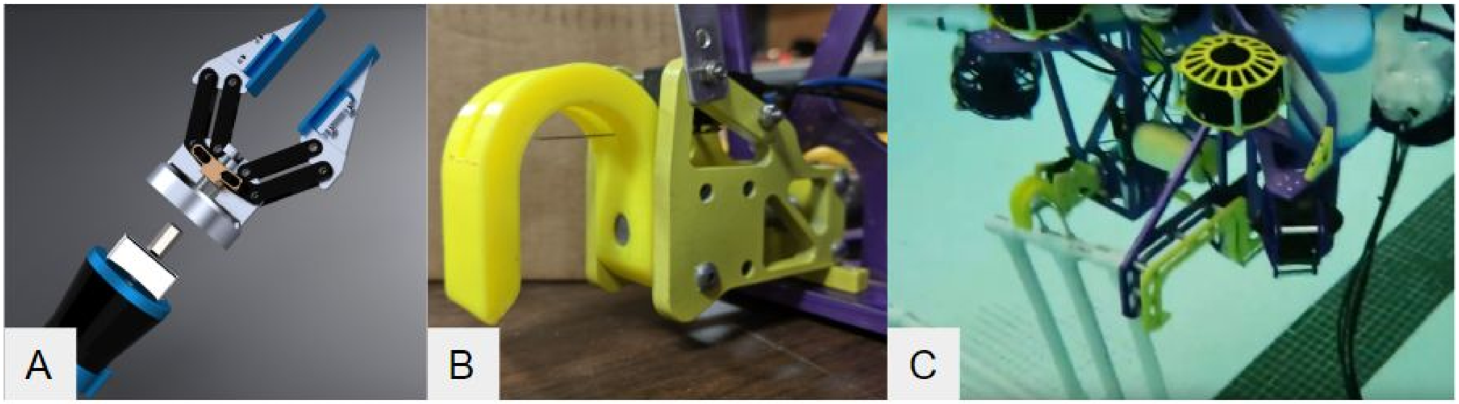


Fig. 15: Manipulator development process.

SmartHook (Primary Manipulator)

The SmartHook is designed to be able to pick up ½" PVC components and U-bolts that are in the horizontal plane in relation to the ROV. Once the inverted "hook" section of the manipulator latches on an object, a pneumatically-actuated shackle extends and traps the object. With this, it is suitable for the following tasks: retrieving the broken trash rack, placing the new trash rack, dropping the reef ball, and moving the rock. The driver has a clear view of the SmartHook from the onboard camera, but the SmartHook can also be automated via a limit switch as shown in *Fig. 15 B*. When the limit switch senses an object, the pneumatic cylinder can automatically actuate.

SmartHook Jumbo & Drop Box

The SmartHook Jumbo and Drop Box subassembly complete three main tasks: recovering the tire, dropping the trout, and dropping the grout. The SmartHook Jumbo is a larger version of the SmartHook for latching onto the tire—the tire is not fully trapped but securely held with a wedge and plate mechanism. In addition, the SmartHook Jumbo releases the trap door for our Drop Box, which can release small items. The SmartHook Jumbo and Drop Box are independent mechanisms actuated by a shared pneumatic cylinder. In order to view the Drop Box in operation, we originally intended to add a secondary camera which would also allow an auxiliary view of the cannon lift system and Micro-ROV. However, we decided this was too complex for the added utility of the auxiliary view and ultimately decided upon a much simpler system for visualization - a rear view mirror. This addition was implemented simply as a bike's rear view mirror attached to the SmartHook Jumbo.

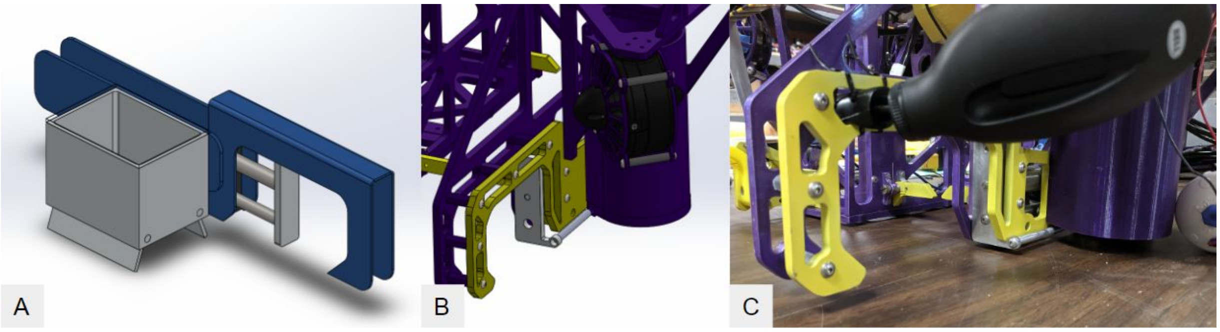


Fig. 16: Smarthook and drop box development: initial model (A), final CAD (B) and final assembly with the rear view mirror (C).

T-Dropper

The T-Dropper system is our chosen solution to hold and deposit the PVC cannon shell markers to mark the ferrous and non-ferrous cannon shells. The T-Dropper does not run off of pneumatic power; instead, it is powered by a waterproof servo. The system consists of a rotary T-storage area made up of two acrylic plates with cutouts to mate to the T profiles. They are additionally held in place with a large 3d printed backstop. This structure stores red and black markers in dedicated sections. Between the two sections there is an opening in the backplate such that when the servo is actuated to take one of the markers sections to that position, it is able to drop out directly under the vehicle.

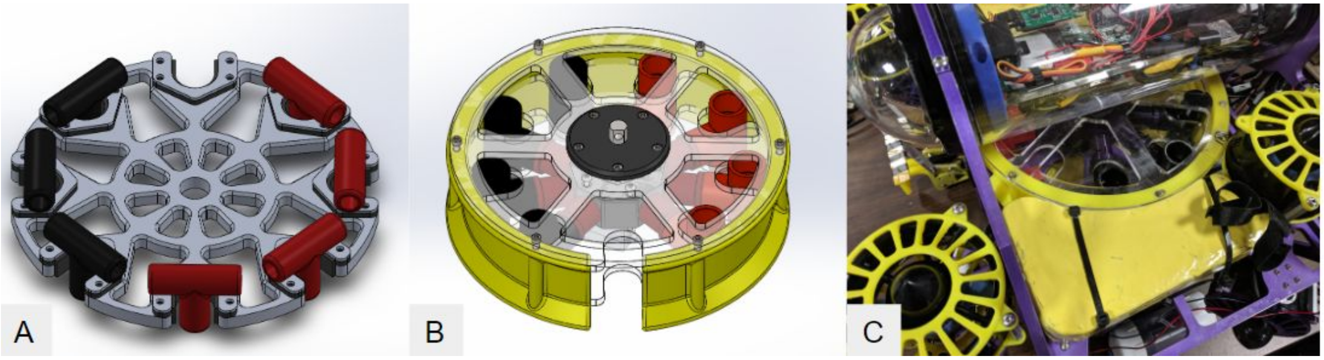


Fig. 17: T-dropper initial CAD concept (A), final CAD, and final assembly within the ROV frame (C).

Micro-ROV

Similar to other systems, we conducted trade studies on a variety of Micro-ROV concepts and proceeded with detailed design for the two best concepts. Initially, we considered two distinct locomotion methods—either a tracked driving vehicle or a thrustered swimming vehicle. In these two categories we also considered multiple options. For a tracked vehicle, the main change was the number of tracks—either 3 with an omnidirectional vehicle, or 2 for a ballasted single directional vehicle. Thruster concepts also varied in number of propulsors. We initially considered a dual-thruster design to allow for steering but decided that that was unnecessarily complex, the system could steer simply by bumping and guiding along the walls of the pipe. Even with the need for steering negated, two thrusters did have benefit in counter rotation meaning no extra action would need to be taken to prevent spinning. However, this was deemed unnecessary with the addition of a simple fin. Ultimately, in detailed design we decided that the simplicity and function of the single-thruster vehicle over the tracked design made more sense for our implementation becoming the final design. To handle recovery of the Micro-ROV, an onboard winch actuated by a waterproofed brushed DC motor is implemented. This recovery system uses a USB slip-ring and fiber-optic USB tether interface.

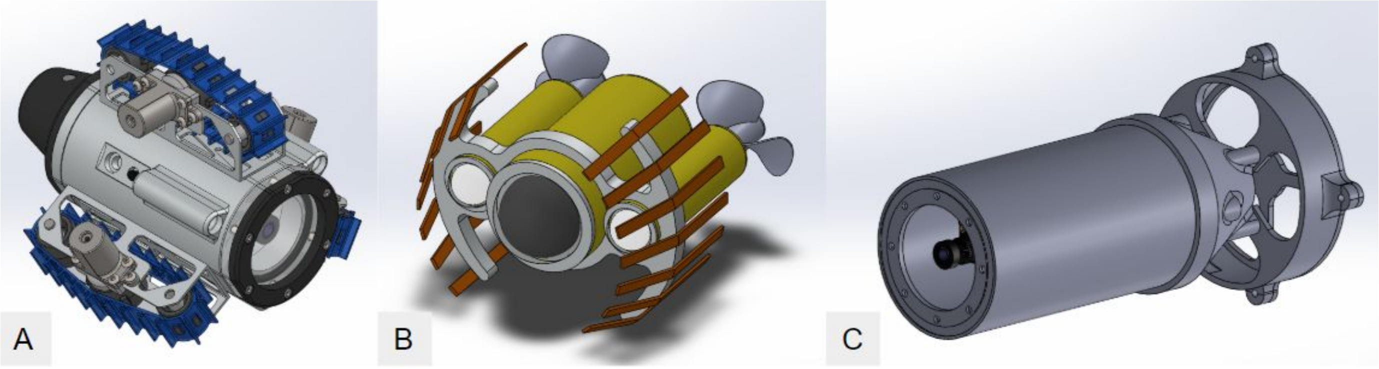


Fig. 18: Initial tracked CAD design (A), initial dual-thruster CAD design (B), final single-thruster CAD design (C).

Cannon Lift System

Our Cannon Lift System is comprised of two main subassemblies—hooks used to hold the cannon, and lift bag systems to give the ROV the additional lift that it needs to return the cannon to the surface. In deciding on the hook system, we performed initial trade studies on a variety of designs and more detailed design on 3 options shown in *Fig. 19* below. Ultimately we decided on a system similarly to B and C, but integrated into the frame to reduce poolside reconfigurations.

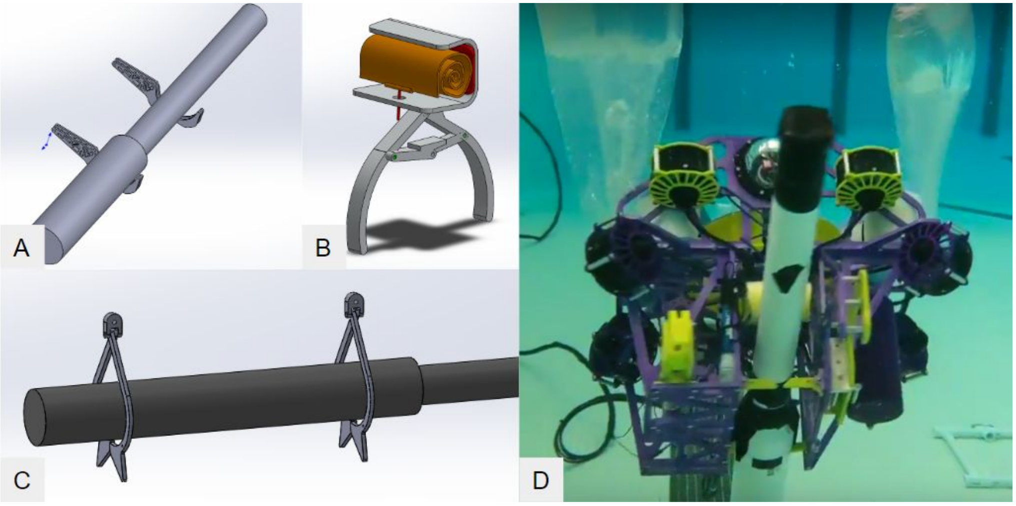


Fig. 19: Various mechanisms considered for lifting the cannon: hooks that flip out from the bow of the vehicle and pick up the cannon from below (A), a spring-loaded gripper to pick up the cannon from above(B), and a modified version of a vertical lift system (C) which was later integrated into the frame as small, spring-loaded fingers (D).

Probes

We opted to use a DS18B20 Digital temperature probe made by Gikfun. The temperature probe is rigidly mounted to the frame.

The pH probe is an American Marine PINPOINT. It is attached to a retractable arm to move it into operating position when needed, and move it out of the way for other missions. The retractable arm is attached to the frame via a shoulder bolt pivot and a *Jergens Kwik-lok-pin* indexes the arm to the desired operating position.

Driver Station

To house our power supply and surface controls, we built a driver control station. This station serves as an all-inclusive cabinet of our power and control elements in order to ensure safe and convenient operation. This cabinet has dedicated shelves for our power supply elements, as well as our pneumatics, and is fully enclosed to protect the operator from fire or electrical hazards. The station also has convenient carrying handles, laptop docking with easily accessible charging and tether access, E-stop, control switches, and tether strain relief. This station has proved to be considerably helpful, as it has simplified our operations, while ensuring our safety standards are met.

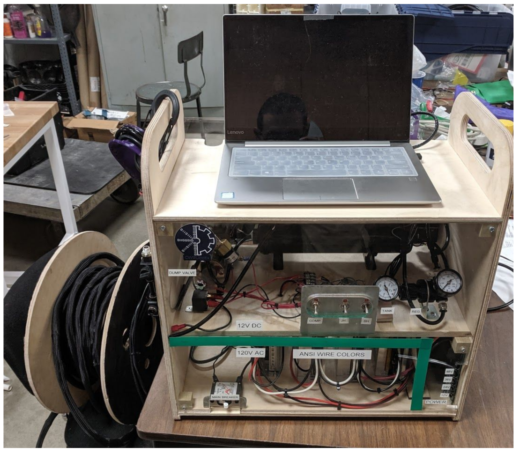


Fig. 20: The Driver Station

Electrical Design Rationale

Subsystem Overview

Our overall electronic design emphasizes cost efficiency as well as plug-and-play ability. These emphases were chosen because they enable us to stay within our budget, while also allowing for ease of troubleshooting and future improvement. Our system is powered by a 48V DC power supply, and controlled via a surface laptop which sends control information across a CAT6 ethernet cable integrated into our tether. Power is sent across two marine grade 14AWG wires with a 30A fuse in series, which is also integrated into our tether. All of our electronics, with exception to our primary buck converter and sensors, are mounted and housed in our watertight electronics bay, which is centered on our frame.

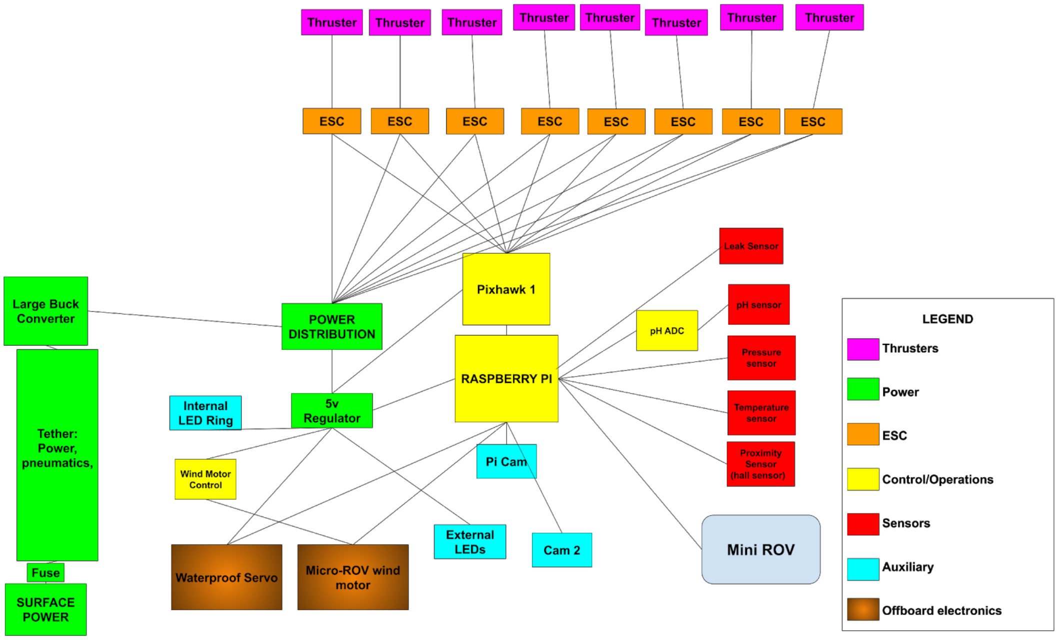


Fig. 21: Main System Block Diagram

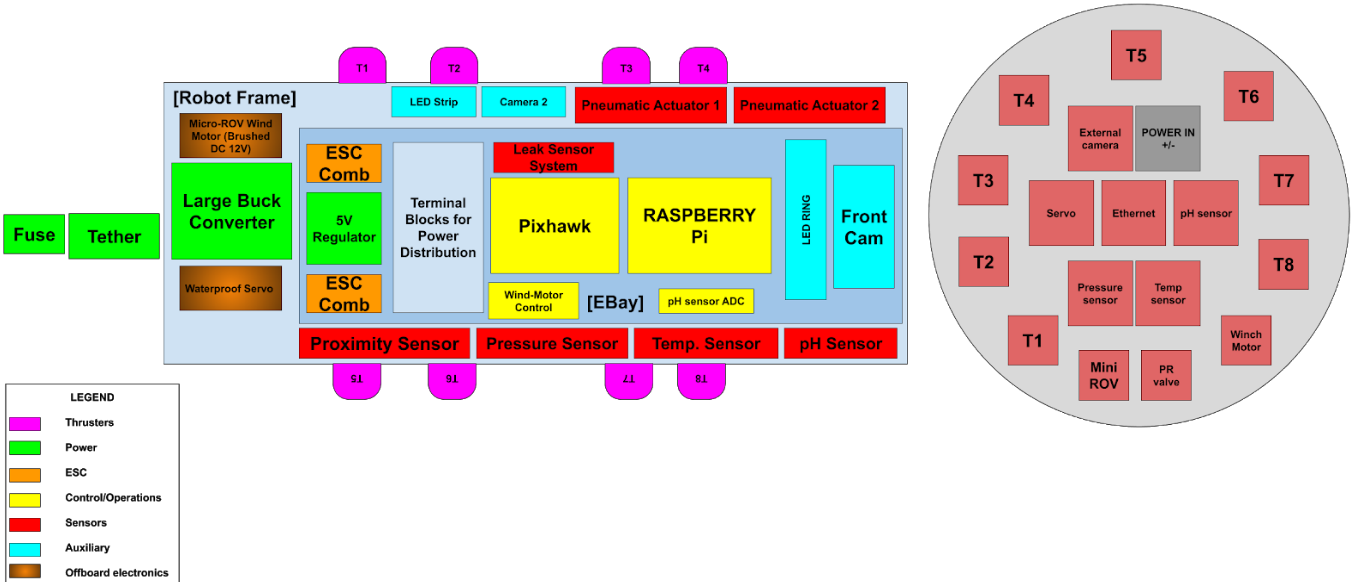


Fig. 22: Main System Hardware Layout

Power Conversion and Distribution

Power is received from the tether by a 48V waterproofed buck converter mounted to our frame that outputs 12V at 30A. This purchased converter was chosen due to its ability to meet our power demands, as well as proving to be more cost effective and reliable than a custom built buck converter. From our primary buck converter, 12V is sent into our E-bay, where it is distributed by a terminal block to our ESCs and thrusters, as well as a secondary buck converter that steps the voltage down to 5V to provide power to our Raspberry Pi, Pixhawk, and auxiliary outputs. Our power distribution system was chosen due to its ease of implementation, small form factor, modularity, and cost efficiency.

ESCs

12V gets sent from our power distribution system to our ESC stack. We utilize eight BlueRobotics Simple ESCs, one for each of our thrusters. These ESCs were chosen due to their cost effective nature, as well as their compatibility with our thrusters and Pixhawk. Their plug-and-play characteristics also allows for ease of troubleshooting and replacement, should one fail during testing.

Thrusters

We chose an 8-thruster configuration using BlueRobotics T100 thrusters. Four of them are mounted vertically on the corners of the frame to provide Z - motion and roll/yaw capability , while the other four are mounted horizontally on the corners with a 45° offset to provide X-Y motion, ultimately providing 6 degrees of freedom. The components were also chosen for their ease of integration into the rest of our system, proven performance and reliability, as well as their ease of control.

Pixhawk

Our system utilizes a Pixhawk Autopilot system that handles our hardware level motion control. The Pixhawk is chosen due to its modular nature, and ease of implementation for the Software Team as it pairs very well with ArduSub, and facilitates ease of control and communication between the surface command station and the ROV. The Pixhawk has onboard sensors, which were critical to achieve automatic stabilization, depth hold, and autonomous line following.

Raspberry Pi

A Raspberry Pi Model 3 B handles temperature and PH sensor data, manages camera feeds, and serves as a companion computer to interface and send high-level motor commands to the Pixhawk. We chose to use a Raspberry Pi due to its ease of programming, as well as the well documented support for sensor and camera integration available. This choice enabled the Software Team to focus more time on the more complex aspects of programming the robot, as the basic sensor and camera data were easily integrated and controlled.

Analog-to-Digital Converter

Our pH sensor required an analog-to-digital converter to be able to use it in conjunction with our Raspberry Pi. To that end, we decided to build a custom ADC, as the commercially available ADCs within budget failed to meet our needs. Basing our design off of the Texas Instruments ADS1120 4-Channel 16 Bit ADC chip, we were able to build a custom ADC that was better tailored to our needs, at an affordable cost.

Ferrous Detection Sensor

In order to accomplish the cannon shell detection task, we decided to build a ferrous detection sensor built off of two linear Hall Effect sensors. These sensors are biased by a magnet, and detect disturbances in the magnetic field resulting from the presence of a ferrous material. This detection then outputs to an amplifier circuit, and a red LED is illuminated. This LED indication is captured by our main camera and is therefore visible to the operator.

Micro-ROV

For our Micro-ROV, we decided to go with a fiber optic tether to handle our communications between the main ROV and the Micro-ROV. This decision was born out of our belief that the additional challenges provided by implementing a fiber optic USB tether would be outweighed by the benefits in competition point performance. To power our Micro-ROV, we are using two 9V batteries in parallel. While other battery formats offered comparable or marginally better performance and lower internal resistance, we chose to use 9V based upon its smaller form factor and ease of implementation. These batteries are attached to a 7.5A fuse, and feed into a 5V regulator to power the Raspberry Pi Zero, which handles our camera feed from the Micro-ROV. The Pi Zero was chosen based upon its small form factor and ease of integration with our camera feed. In addition, we have LEDs connected to the 5V regulator to illuminate the Micro-ROV's path with enough light for the camera to provide the operator with a usable image.

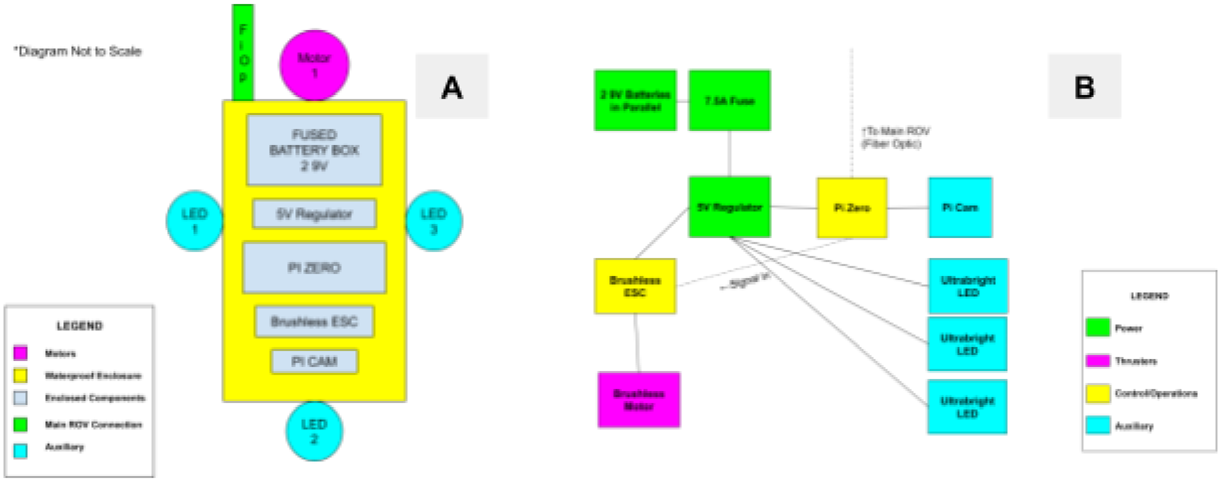


Fig. 23: Micro-ROV Hardware Layout (A), Micro-ROV Block Diagram (B).

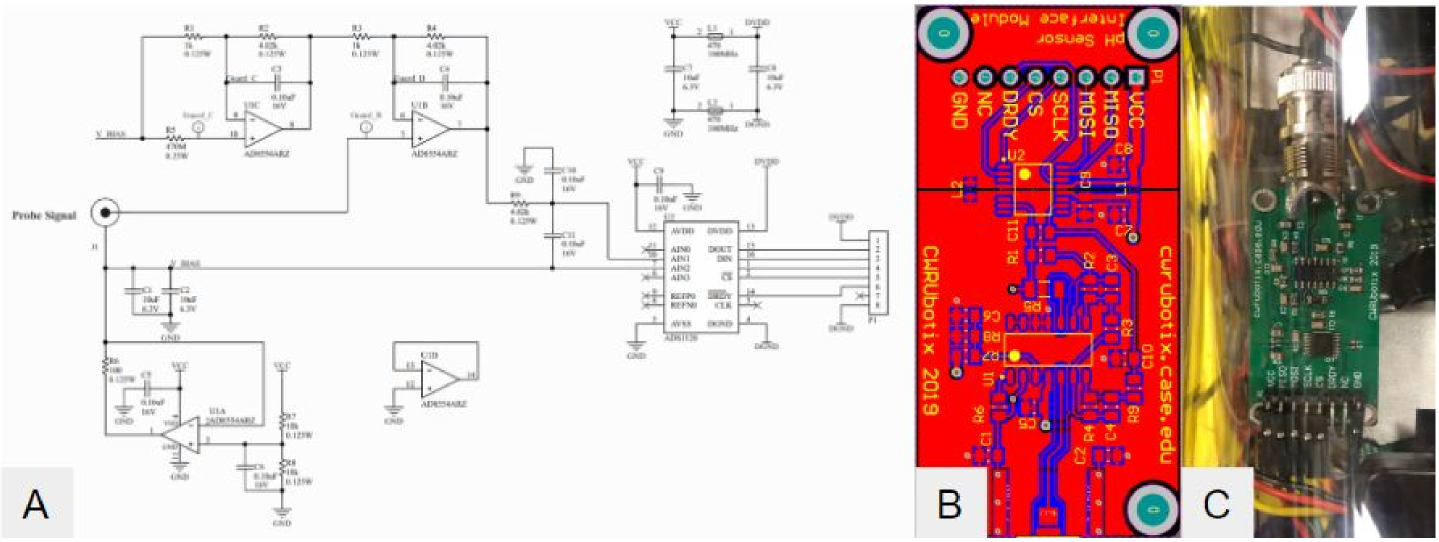


Fig. 24: ADC Schematic (A), layout (B), and completed board (C) .

Software Design

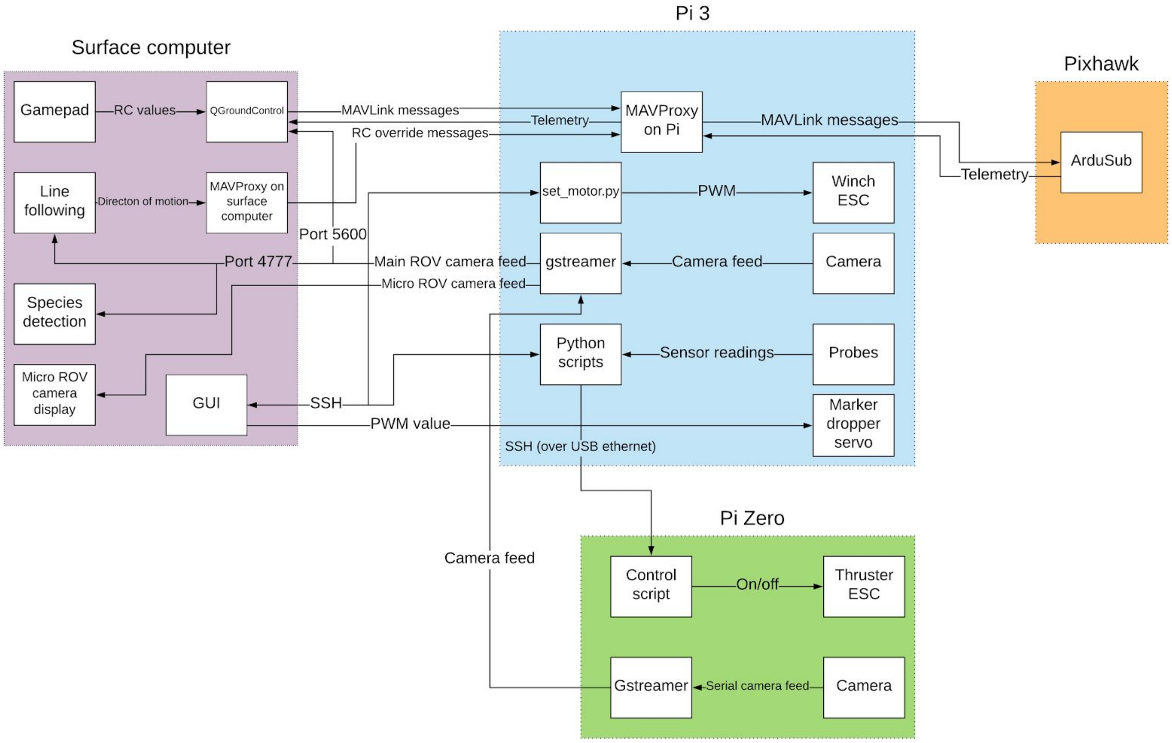


Fig. 25: Software block diagram.

Subsystem Overview

The control software runs on four different computing devices: the surface control computer, the Pixhawk, the Raspberry Pi 3, and the Raspberry Pi Zero. Operator control of the ROV is implemented via an ethernet connection between the surface computer and the Pi 3, and then a USB serial connection between the Pi 3 and the Pixhawk, as required by ArduSub. Cameras are streamed back to the surface computer using GStreamer running on the Pi 3 and Pi Zero. All other motors, as well as sensor readings, are controlled via terminal commands over SSH. This was chosen due to the fact that SSH is a simple protocol which is natively supported on all Linux systems. A more control-specific protocol such as MAVLink would greatly increase complexity with little benefit.

Surface control station

The surface control station consists of a laptop running QGroundControl and our custom SSH control interface, as well as a USB Xbox 360 controller. The robot's motion is controlled using the native capabilities of ArduSub and QGroundControl using the gamepad sticks.

SSH interface

The Micro-ROV, winch, and marker dropper are controlled from a Python script, which is controlled with keyboard input, that executes pigpio terminal commands. For control of the mini-ROV, a 2-hop SSH channel is opened to the Pi Zero through the Pi 3; for the others, a standard SSH channel is opened to the Pi 3. Using the `pigs` command, GPIO pins are set to output the necessary PWM values. The temperature sensor and pH sensor are both read with Python scripts using the `pigpio` Python library, which read the correct GPIO pins and return values to the control window. The pH probe requires an additional setup step, which is also executed through the command line to configure the ADC for transmission of the reading over SPI. Additionally, both camera feeds can be simultaneously viewed through our control interface.

Benthic species identification

The image is first captured and saved from the OpenCV video stream window, as implemented in Python. The image of the benthic species is then manually cropped and passed to the Python script for image recognition. Within the script, the image is first converted to grayscale and then converted to a binary black and white image using Otsu thresholding. Contour detection is then used to detect the outlines of the different shapes, and any contours whose area is less than 0.001 times the area of the entire image are discarded as noise. The RDP algorithm, as implemented in the OpenCV `approxPolyDP()` function, is then used to reduce the number of edges in each contour, which is then used to identify each shape. Finally, the number of each shape is displayed on the screen.

Autonomous line following

The camera feed is captured by OpenCV in Python. A child process is spawned which constantly commands the ROV to move in the direction determined by the line-following algorithm, which can be UP, DOWN, LEFT, RIGHT, or STOP. The parent process calls the update method when each frame is received, which updates a variable accessible to the child process. Inside the update method, a frame is captured from the video stream. It is masked and thresholded in order to find the color red, and then the `findContour` function is called on the masked image. The start and end are handled as special cases, but in all cases, the largest contour is assumed to be the line. While in motion, the program calculates the ratio of the area of the red contour's bounding rectangle to the area of its convex hull. If the ratio is close to 1, it is considered to be a straight section, and the ROV is commanded to keep moving in the same direction. Otherwise, it is considered to be a turn, and the direction of turn is determined based on the current direction and the orientation of the convex hull. We also keep track of the position of the centroid of the red contour in order to track its position in the frame. If no red contour is visible in the frame, the ROV will be commanded to move back in the direction in which it lost the line. Once the line is re-acquired, the ROV will continue following the line as before.

At the start, the ROV is positioned under operator control, and the autonomous sequence is started. The ROV will move toward whichever side of the frame the bounding box of the red contour touches. At the end, the ROV will stop when it detects an ending shape.

Crack measurement

The crack measurement function is called at the same time as autonomous line following. Given a frame from the camera feed, a binary mask is first applied using HSV thresholding in order to detect the color blue. The OpenCV `findContours()` function is then used to detect contours in the masked image. The largest contour, provided its area is above a certain threshold, is assumed to be the crack. There are two methods implemented for determining the crack lengths. The first is the ratio method in which we compare the size of the crack to the assumed ideal width of the tape. The second, preferred method of measurement is via a perspective transform. The lines on the grid are detected with masking and a Hough line transform, and then a perspective transform is applied to the largest contour. The perspective transform uses the fact that the grid lines form 30 cm squares, and transforms the image to make the grid lines form a square. The crack length is then calculated based on the pixel distance between grid lines. If at any point the perspective-transform method cannot be used, the function reverts to the ratio method.

Crack mapping

As the ROV follows the red line on the dam, a mapping function is called whenever a new frame is received. On each function call, it first applies a Gaussian blur to reduce noise, and then applies a mask to remove possible interference from other elements in the image. A Hough line transform is then used to detect the grid lines, and line crossings are counted in order to determine the current grid square. Vertical and horizontal lines are counted separately, and this is done by assuming that the line closest to the position of a line in the previous frame is the same line. This allows us to track lines as the ROV crosses them, and when a line crosses the center of the frame, that is counted as a line crossing, and the ROV's grid position is incremented based on the apparent motion of the line. When the crack is detected, the current grid square is retrieved and displayed on the screen.

Testing, Troubleshooting, and Technical Challenges

Mechanical System

Mechanical systems were tested initially during dry conditions to verify that components were performing as expected. Particular attention was given to mechanisms using rotating and sliding surfaces with the highest potential for binding or jamming failures and seals and assemblies that were critical to prevent water ingress. Once it was confirmed that these systems were performing in the air, mechanical systems were tested over a series of wet-run trials to verify final function. In water, the mechanical team had to quickly resolve issues with loss of buoyancy, stabilization, mechanical lift bag failures, and low-rate leaks into our ebay. Systems that failed were completely or partially redesigned based on real-world in-water weight and other data determined in testing.

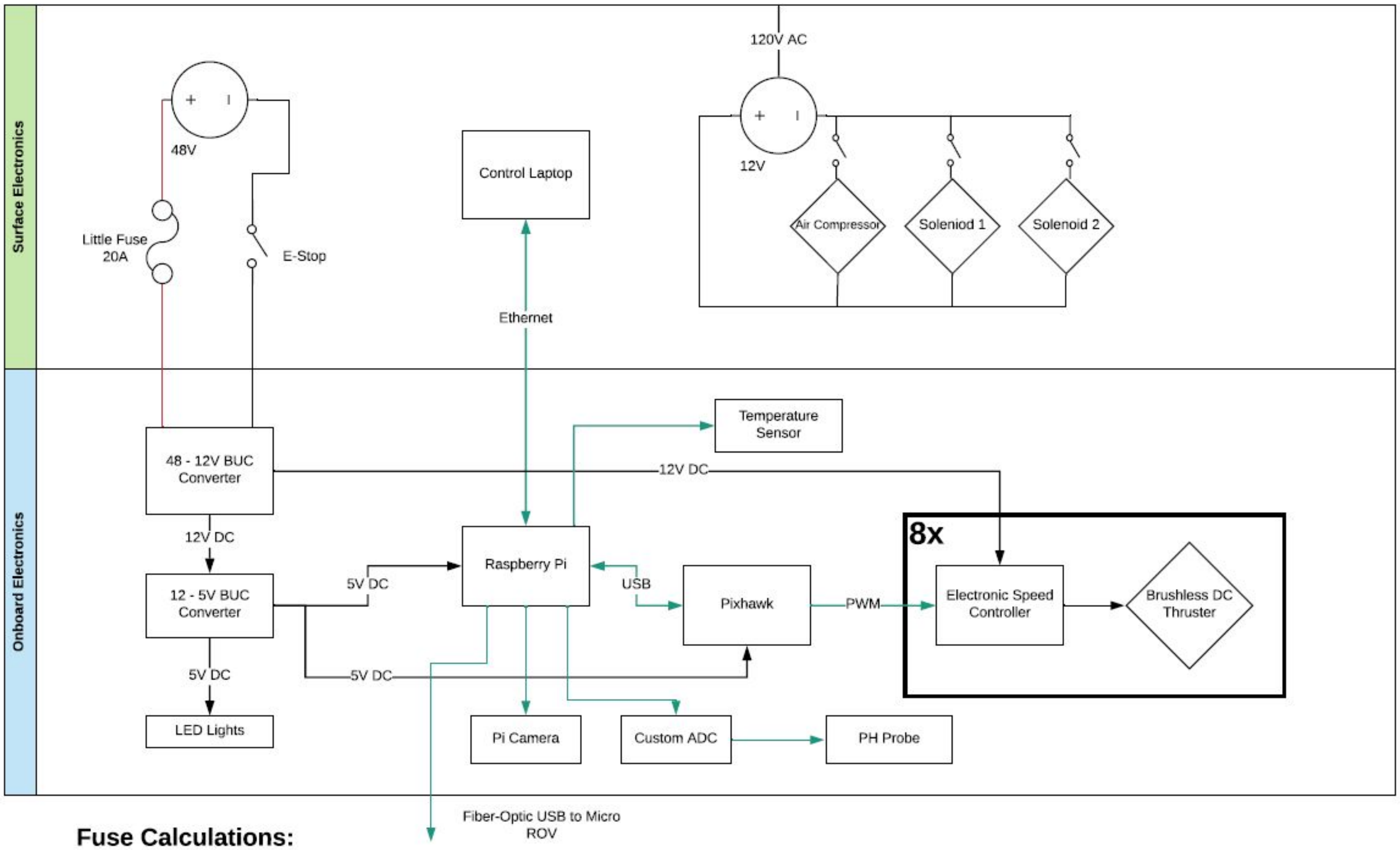
Hardware System

The robot's electrical system was first tested under dry conditions with components laid out on a bench to aid the testing and debugging process. After wiring fixes and power-up tests, primary systems were determined to be online and were installed in the E-bay and mounted to the electronics sled. Once it was confirmed that these systems were performing in the air, the electrical system was put through initial wet-run trials to verify core functionality. As the testing phase evolved, secondary systems for sensor data collection, lights, etc. were brought online. As consistency issues arose with system performance, the electrical team had to quickly and safely review wiring, debug their custom PCBs, and resolve brown-out power issues with the onboard buck converter that ultimately were determined to be caused by a defective unit.

Software System

Before the ROV was tested in water, all software had been tested on videos and still images, taken both in air and underwater, of the dam and benthic species. The ROV's motion in the water was not as ideal as what had been assumed. The motion was corrected for in the line-following software to allow the ROV to get back on track if the line was no longer in frame. The image processing code was re-tuned to correct for the optical conditions of the pool. PID parameters also required adjustment in order to optimize ArduSub's Stabilize control mode. Additionally, the pH sensor required debugging due to a nonstandard ADC configuration.

System Integration Diagrams



Fuse Calculations:

Total Power Draw: Thrusters 960W + Ebay Control Electronics 19W + Light 6W
=> Input current draw = 360W / 48 V = 20.5 A
=> Ideal Fuse Rating = 20.52 * 1.25 = 25.65
=> 30 A Fuse is selected as the closest availible size from the three options required per the manual

CWRUbotix - Electrical SID

Fig. 26: Main Electrical System Integration Diagram

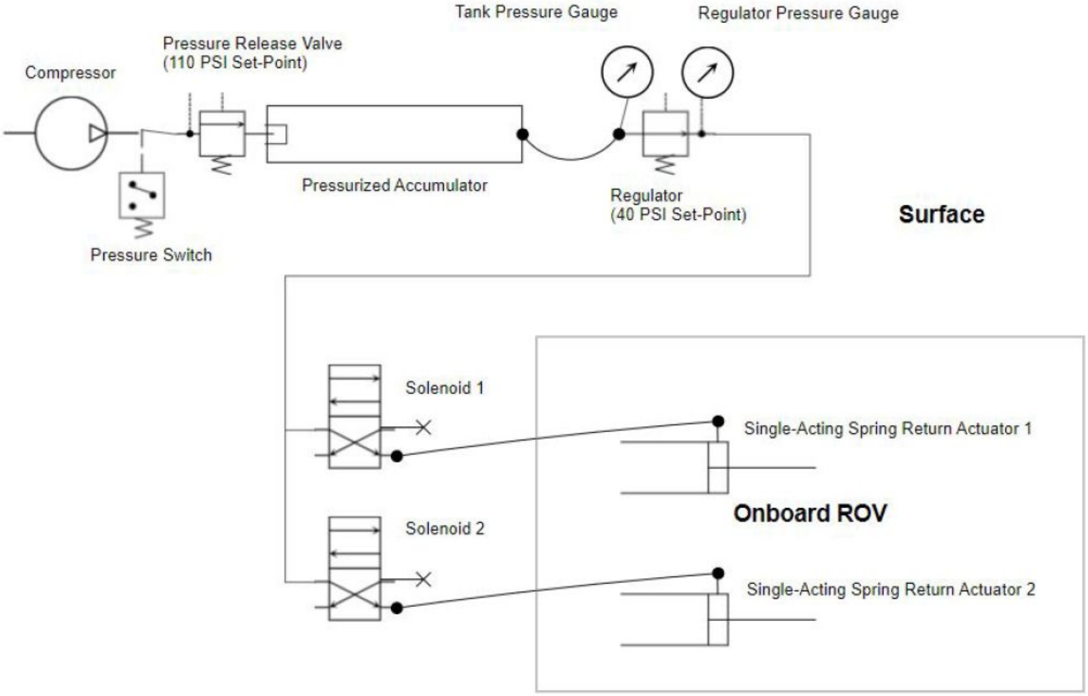
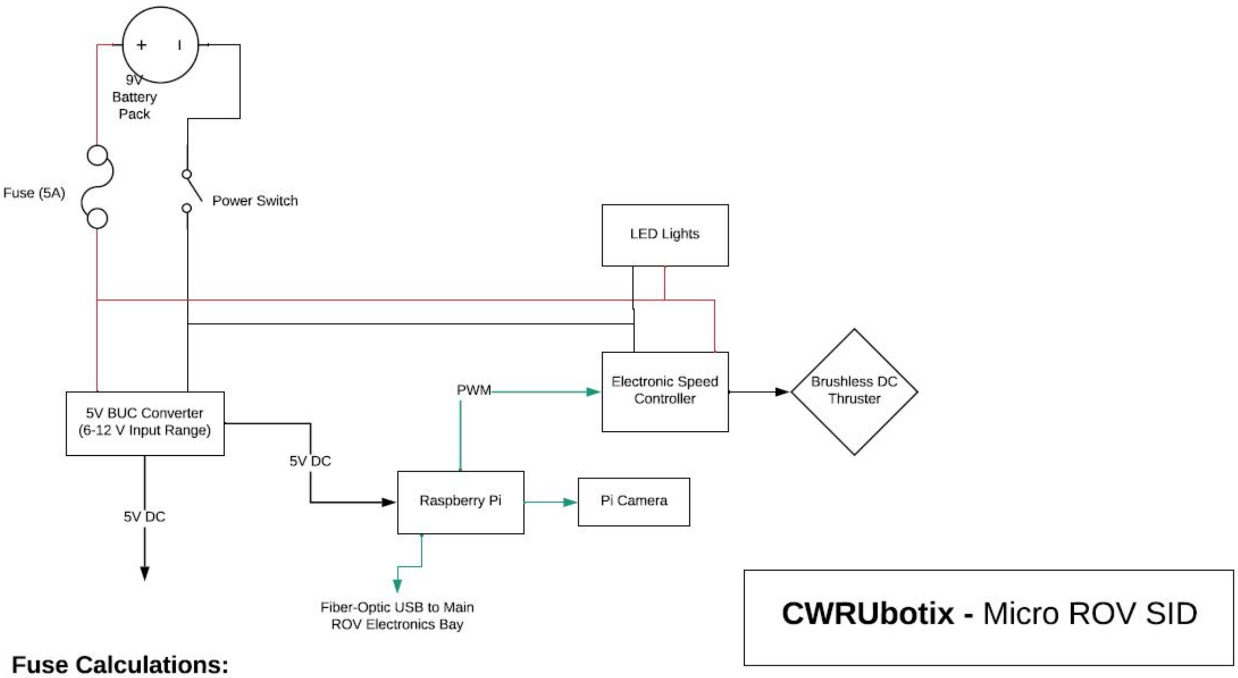


Fig. 27: Fluid Power System Integration Diagram



Fuse Calculations:

Total Current Draw of the System = Thurster 2.3A + Pi 550mA + LEDS 100mA + Pi Camera 250mA = 3.2 A
=> Ideal Fuse Rating = 4.2A * 1.25 = 6.3 A
=> 7.5 A Fuse is selected as the closest availible size in an apporiately rated form-factor

Fig. 28: Micro-ROV System Integration Diagram

Conclusion

Lessons Learned

One of our hardest lessons learned as a rookie company was in the testing phase of the project. While making relatively small but last minute to changes to our system, a few of those changes resulted in a cascading failure during an informal product demonstration session. While all of these changes were routine procedures that had been done successfully before, minor mistakes were overlooked, leading to water entering our E-bay. While this failure didn't result in any permanent damage to the vehicle, it altered our modification and vehicle preparation procedures for product demonstrations. In a similar vein, some initial testing wasn't performed at full depth or with fully accurate mission props resulting in unexpected design changes.

Another difficult lesson learned regards vendor selection and the need to be more critical of who we choose. When designing the Micro-ROV, we fairly quickly realized that a slip ring would be required for neat onboard tether management. We also realized that standard slip rings were out of our budget. We did research and asked for quotes and sponsorship from a number of companies, both US and international. Ultimately, we decided to order one from Senring Electronics, who would give us a small discount. Unfortunately, there was significant miscommunication between our university's Mechanical Engineering Department (whom we ordered through) and Senring that led to delays in the placement of the order. Ultimately, we ordered it on our own and it arrived the day that we left for our first product demonstration. In the future, we will more carefully choose companies who we are ordering from to avoid such logistical issues or where long lead times are unavoidable, plan further in advance.

As a rookie team, we have learned a tremendous amount and have a long list of future improvements and things to try. Some highlighted planned improvements include custom high-lumen LED lights for better vision and more consistent color for image processing, an onboard solenoid system for more flexible pneumatic configurations, and improving the reliability of our buoyancy fabrication process.

Appendix

References

0033mer. "Build Your Own Proximity Sensor." YouTube. December 20, 2017. Accessed March 22, 2019. https://www.youtube.com/watch?v=9wyeogsahag&t=113s.

"ArduSub GitBook." ArduSub Project. https://www.ardusub.com/

Button, Clar. "Building Your ROV A Manual for High School." Eastern Edge Robotics (2010).

CES Edupack 2016. 2017. Windows. Cambridge: Granta.

Granville, Paul S. Elements of the drag of underwater bodies. No. SPD-672-01. DAVID W TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER BETHESDA MD SHIP PERFORMANCE DEPT, 1976.

Ishitsuka, Makoto, and Kazuo Ishii. "Development of an underwater manipulator mounted for an AUV." In *Proceedings of OCEANS 2005 MTS/IEEE*, pp. 1811-1816. IEEE, 2005.

MATE. "MATE ROV Competition Manual." EXPLORER 2019 (2019).

MATE. MATE ROV 2018-2019 Innovations for Inshore. 2019. http://forums.marinetech2.org/index.php

"Mechanical Movements." 507 Mechanical Movements. Accessed May 24, 2019. http://507movements.com/.

"NanoMag™ | One of the Smallest Magnetic Robot Inspection Crawlers." Inuktun Services Ltd. Accessed May 24, 2019. http://inuktun.com/en/products/onsite-standard-products/nanomag-miniature-magnetic-crawler/.

"T100 Thruster." Blue Robotics. http://www.bluerobotics.com/store/thrusters/t100-thruster/.

Techet, Alexandra Hughes. "13.012 Hydrodynamics for Ocean Engineering, Fall 2002." (2002).

Parker O-ring handbook. Lexington, KY: Parker Seal Group, O-Ring Division, 2001.

Rosenbrock, Adrian. "OpenCV shape detection." PyImageResearch. https://www.pyimagesearch.com/2016/02/08/opencv-shape-detection/

Turbo, MAN Diesel. "Basic principles of ship propulsion." Saatavissa: https://marine. man. eu/docs/librariesprovider6/propeller-aftship/basicprinciples-of-propulsion. pdf (2011)

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- Saevar Theodorson, for letting us use his pool for testing.
- Kenneth, for aiding in the debugging of our ferrous detection sensor.
- Our sponsors the Case Alumni Association, Sears think[box], and Jergens, inc. A full list of CWRUbotix sponsors is available on our team website.