ROVOTICS
JESUIT HIGH SCHOOL ROBOTICS

BOXFISH

JESUIT HIGH SCHOOL
CARMICHAEL, CA
MATE 2019

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INTRODUCTION

ABSTRACT

Rovotics' newest innovation, *Boxfish*, is an underwater Remotely Operated Vehicle (ROV) designed to excel in tasks relating to lakes and rivers. *Boxfish* is fully equipped with tools to determine habitat diversity, recover historical artifacts, as well as to repair and autonomously monitor dams. Rovotics (Figure 1), a seventeen-person company, has the technical skill and experience to produce ROVs designed to meet and adapt to various requirements. Organized into interdependent departments by specialty, Rovotics efficiently oversees product development in an organized way.

Boxfish is the result of months of planning, research and development, manufacturing, and testing under strict quality and safety standards. The ROV is designed for serviceability, increased speed, maneuverability, and power efficiency. Features such as a modular and lightweight frame, reliable electronics, and a new extensible software platform make *Boxfish* our most advanced vehicle yet. This technical document describes the development process and design details that make *Boxfish* the best ROV for ensuring public safety, maintaining healthy waterways, and recovering essential historical artifacts to meet Eastman Chemical Company's Request For Proposal (RFP).

Figure 1. Rovotics Team Members

ROVOTICS
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TABLE OF CONTENTS

DESIGN RATIONALE

DESIGN EVOLUTION

Rovotics has re-evaluated design requirements and decided to focus on cost-effectiveness, adaptability, and reliability in the design of *Boxfish*. *Boxfish* is the next step in the evolution of Rovotics' product line and is constructed based off of many years of experience building and refining ROVs tailored to meet customers' needs. Analyzing the successes and shortcomings of previous designs allowed employees to make significant improvements to the ROV and Rovotics' design process. This led to several key innovations in ROV design, including a Robot Operating System (ROS) based software architecture, a thermally-isolated Power Systems Enclosure (PSE), an inexpensive, durable, space-efficient Main Electronics Enclosure (MEE), and a modular, lightweight frame (Figure 2).

Safety continues to be Rovotics' top priority. Along with Rovotics' standard array of electrical safety features, Rovotics has introduced a greater level of system redundancy and software crash protection that allows the ROV to take the proper course of action in the event of a system failure. Smart software algorithms monitor sensor readings across the entire system to detect and address abnormalities.

Rovotics also integrated component-level testing more thoroughly into our design and development process this year. New electronics and software were tested on tabletop test platforms before being implemented onto our production ROV. A new Gazebo ROV simula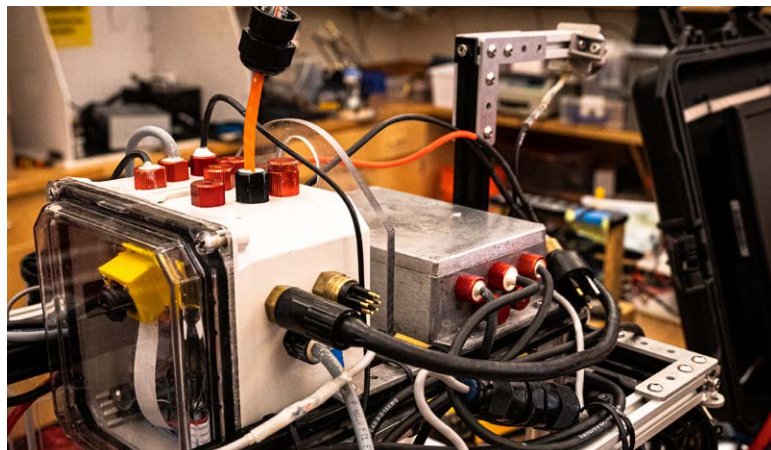tion allowed Rovotics to fully test software systems and autonomous algorithms independent of hardware. Purchased components, such as thrusters or electronics housings, were tested thoroughly before implementation onto the production ROV to safeguard against failures. Structural aspects, such as buoyancy and watertightness, were verified before the design was finalized. These and other improvements are discussed in further detail in the sections that follow.

Every manufacturer must consider "make/buy" decisions during the product development process. Rovotics considered build time, cost, and reliability when deciding whether to incorporate off-the-shelf components or manufacture custom solutions. For components such as the MEE and PSE, Rovotics decided it was more cost-effective, time-efficient, and reliable to purchase pre-made components that could be tailored to fit our needs, rather than designing and manufacturing them from the ground up.

MECHANICAL DESIGN AND MANUFACTURING PROCESS

To streamline design and development, Rovotics used a parallel design process that allowed the mechanical design and manufacturing departments to envision end results early and produce high-quality, effective components. This process helped reduce the number of miscalculations, omissions, and revisions.

The design process began with group brainstorming in front of a whiteboard, displaying and discussing ideas for completing each task and requirement. Concepts were judged based on size, weight, effectiveness, cost, complexity, ease of manufacturing, safety, serviceability, and reliability on a decision matrix resulting in designs which best fit the RFP requirements (Figure 3). Once each
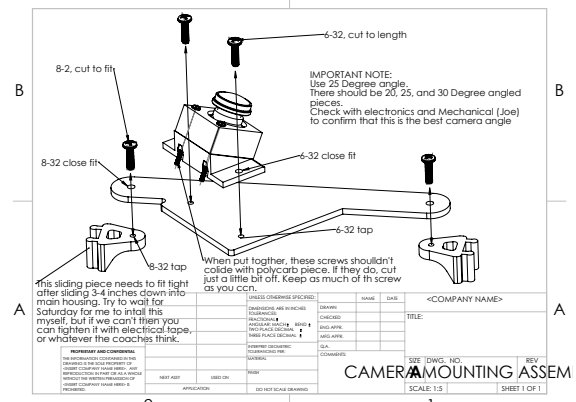

Figure 2. The new PSE and MEE

Figure 3. Camera Assembly from the Design Process

design concept was agreed on, an employee assigned to the component used Rovotics' Plan, Build, Test, and Release (PBTR) process to efficiently design, manufacture, and integrate the new design onto the ROV.

The manufacturing process began with a proof of concept consisting of either a cardboard mockup or a Computer-Aided Design (CAD) model (Figure 4). Once the proof of concept was created, the manufacturing department reconvened to debate the model's viability before the final product was fabricated.

Figure 4. Boxfish's *CAD*

After the proof of concept was checked off and validated by a lead, parts set to be produced on a Computer Numerical Control (CNC) mill were converted from CAD to "G-code" using a Computer-Aided Manufacturing (CAM) package, such as SheetCam. For parts manufactured by hand, 1:1 CAD drawings were printed out to act as templates for fabrication. Any parts too complex to be machined by hand or cut by the CNC were 3D printed.

After parts were manufactured, they underwent component and integration testing, ensuring the parts' safety, serviceability, and reliability. Once a part passed the testing stage, it was released onto the ROV's final assembly.

MECHANICAL COMPONENTS

Frame

Rovotics has completely rethought the ROV frame design. This has resulted in an agile, modular, and versatile frame built from simple and reusable off-the-shelf components (Figure 5).

The top frame is made out of 20mm x 20 mm extruded aluminum bars that facilitate quick fabrication and adjustments. The bars cost $6 per meter, which makes them more cost and time effective than previously used machined frame parts. Because of the channels
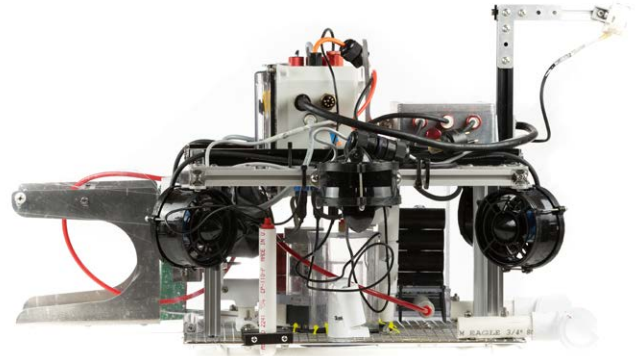

Figure 5. Boxfish's *Frame*

on the bars, each component is able to be quickly reconfigured or moved around the frame.

The Main Electronics Enclosure (MEE) and Power Systems Enclosure (PSE) are mounted to the top frame. The MEE is an off-the-shelf polycarbonate box chosen because of its short lead time and more secure face seal compared to bayonet seals featured in past tube designs. The PSE is a cast aluminum box and was chosen because of its high thermal conductivity which is used to cool both the Electronic Speed Controllers (ESC) and voltage converters.

For stable vector drive, horizontal thrusters are mounted at 45° on each of the four corners and two vertical thrusters are mounted on either side of the ROV. The center of mass is aligned with the center of thrust to maximize ROV stability. Because of the versatility of the frame design, thruster placement can be adjusted to fit the ROV's specific center of mass.

The tool deck is made out of a lightweight steel grid (cookie cooling rack) that enables a flexible tool layout and maintains a low drag profile. Each tool can be quickly moved around the grid system by adding a washer and nut to secure the tool to the deck. The tool deck itself is removable from the top frame with just four screws, allowing employees to work on the top frame separately from the tool deck.

Electronics Housing

Through data collection, analysis, and testing, Rovotics found that square electronics housings could be waterproofed with a higher degree of reliability and were easier to manufacture and service than cylindrical housings. As a result, the new electronics enclosures can be serviced much faster than previous ones.

The new electronics housing addresses thermal issues by splitting electronics into two different housings: the Power Systems Enclosure (PSE) and the Main Electronics Enclosure (MEE). To address the heat generated by the ESCs and the voltage converters, the aluminum PSE doubles as a heat sink (Figure 6). The voltage converters, which are responsible for generating the majority of heat in the system, were aligned on the aluminum walls of the PSE to maximize thermal transfer to the water. This new method brought average voltage converter operating temperatures down from 80° C to 35° C. This improves the lifespan of the electronics and allows for continuous operation of the ROV at peak performance.

The cast polycarbonate MEE contains the core ROV computational systems and has a clear lid to allow
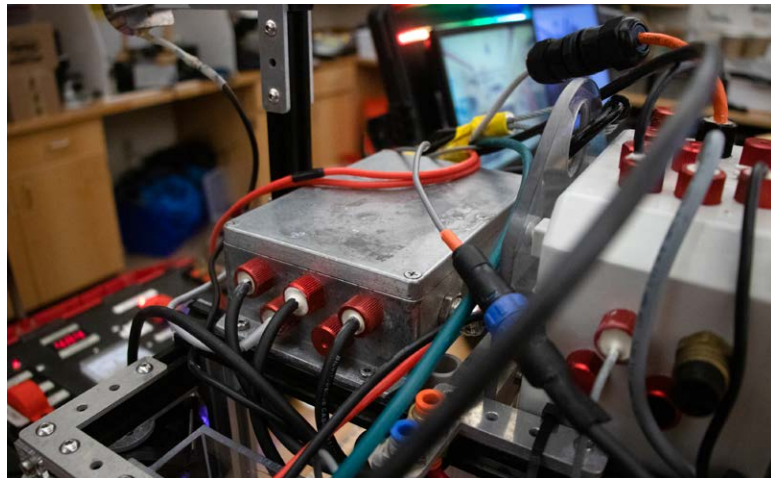

Figure 6. Boxfish's *PSE*

for an internal 110° Field of View (FOV) digital camera. The clear lid also allows for visual inspection of the electronics. Inside the MEE, a modular sliding shelf system provides for easy access and modification to internal components.

The connector layout of the PSE and MEE complement their form-factor and serviceability. During manufacturing, 10 mm holes were drilled into the housing to allow for the addition of future electrical connections by simply potting a new cable penetrator. Holes not in use can be easily capped with minimal impact on reliability. The MEE and the PSE are connected through an 8-pin SubConn connector that facilitates power and data communication between the two housings. The housings can be separated from the frame independently by disconnecting the SubConn.

Thrusters

Boxfish is equipped with six T100 12V Blue Robotics thrusters. The T100 thrusters were chosen for their low weight, affordability, and reliability on previous Rovotics' designs. Last year's design, *Mako*, used four T100 thrusters and two T200 thrusters; however, the additional $50 cost of the T200s over the T100s was not justified by the little benefit provided. Additionally, the standardization in thrusters eliminates the costs of having two different types of backup thrusters.

To achieve stable vector drive, four T100 thrusters are mounted at 45° angles at the corners, allowing all thrusters to contribute to the total propulsion in the cardinal directions and minimize flow interference with components in the center of the vehicle. The T100 thrusters operate at a maximum power of 150W, well within *Boxfish's* power budget.

For the safety of personnel and equipment, thruster guards are mounted on both sides of the thrusters' core nozzles to prevent foreign objects from entering the thrusters (Figure 7).

Figure 7. Thruster Guards

Item	Quantity	Density kg/m^3	Volume m^3	Bouyant Force (N)	Total Weight in Air (N)	Total Weight in Water (N)
20:20 extrusion (per m)	210	2700	0.0000049	10.0842	27.22734	17.14314
Aluminum Brackets	1	2700	0.000016	0.1568	0.42336	0.26656
Electronic Enclosure	1		0.00358	35.084	10.927	-24.157
Electronics	1		-		0.025	2.548
Power Enclosure	1		0.001125	11.025	6.8404	-4.1846
Trout/Grout motor	1		0.000204	1.9992	3.1164	1.1172
T-100 Thrusters 295g / 120g ea	6		-		17.346	7.056
Additional Mission Tools					39.2	25.97
Total					105.1055	25.7593

Amount of additional bouyancy needed: volume = 25.8N / (1000kg * 9.8m/s^2 - density of foam kg/m^3 *9.8m/s^2)

0.00326 m^3 = 25.8N / (1000kg * 9.8m/s^2 - 192 kg/m^3 *9.8)

Figure 8. Buoyancy Spreadsheet

Buoyancy

Boxfish and its tether have a displacement of approximately 14,500 cm^3. *Boxfish* has three main buoyancy components: the electronics housings, foam buoyancy, and water bottles. Based on Archimedes Principle, the electronics housing contributes over 4.7 N of positive buoyancy to the ROV. A combination of foam and water bottles provide the remainder of the buoyancy.

A spreadsheet (Figure 8) was made to record the displacements and densities of each part of the ROV. This data was used in calculating *Boxfish's* weight in both air and water. Once the majority of the ROV was manufactured and assembled, the actual and calculated values were compared so buoyancy devices could be fine-tuned.

Buoyancy is added to the tether using water bottles at strategically-spaced increments along its length. These chambers, which have been used successfully on previous generations of Rovotics' products, have proven to be incompressible at depths exceeding 13 m. The tether is designed to be buoyant enough to keep it from interfering with the ROV while not being so buoyant that it impedes ROV motion.

ELECTRICAL SYSTEMS

Topside Control Unit (TCU)

One of Rovotics' major investments last year was in the TCU. Due to its success, Rovotics decided to reuse most of last year's TCU and focus development efforts on the ROV.

The TCU (Figure 9) was designed to fit in a Pelican iM3220 case that allows for easy transportation, setup, and protection due to its durable and mobile design. Two 60 cm monitors are mounted on the top of the case and are plugged directly into the Intel NUC, a powerful yet compact computer, housed in the bottom compartment. This is an upgrade from last year's UDOO X86, which didn't have enough computational power nor reliable driver support for this year's software. The monitors and Intel NUC allow for more advanced graphics in the software Graphical User Interface (GUI). An adaptable 25.6 cm touch screen was installed into the bottom of the TCU for easy and customizable communication between the operators and the ROV system. A digital button on the touch screen controls power on/off to the ROV through a 120A relay. A Blue Sea Systems power switch has also

Figure 9. The TCU

been implemented as a safety feature to quickly shut down the ROV.

The TCU's bottom compartment was designed with a liftable lid in order to be easily serviceable. Designated mounting panels and wiring channels also ensure an organized and modular construction. The Intel NUC serves as the main computer for the topside control system. It communicates to all subsystems through a routed Transmission Control Protocol (TCP) / User Datagram Protocol (UDP) communication. Networking systems such as the router and the ethernet switch are contained within the TCU. The keyboard, mouse, joystick, and throttle connect to the Intel NUC through a USB hub stored in the TCU.

A custom Printed Circuit Board Assembly (PCBA) streamlined the wiring and allowed for more serviceability and expandability through screw terminal connections
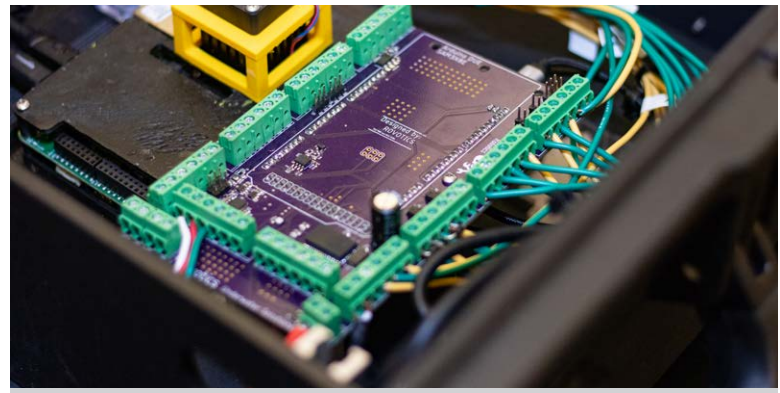

Figure 10. The TCU's custom PCBA

(Figure 10). The TCU board is controlled by an Arduino DUE, which manages the majority of General Purpose Input Output (GPIO) and switching functionality while also controlling a smaller microcontroller that manages the TCU's onboard RGB status LEDs. A temperature/
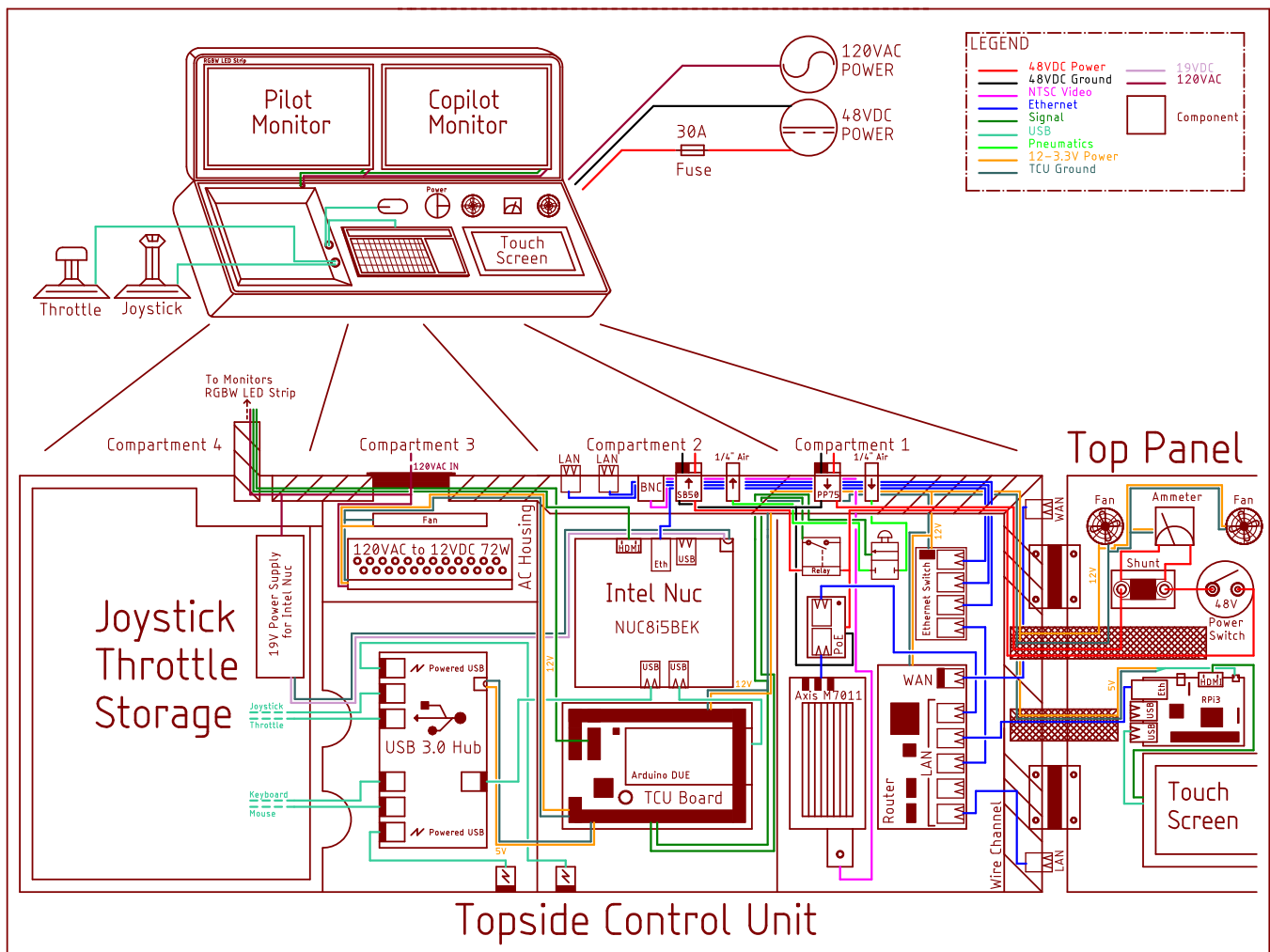

Figure 11. TCU SID

humidity sensor and a current sensor send data to the Arduino DUE. To decrease the topside load on the power budget and to allow for the TCU to be booted without an external power supply, Rovotics used 120V AC in the TCU. The 120V AC is responsible for powering all major topside processing and display equipment and is immediately converted down to 12V DC in an isolated AC housing.

The back of the TCU contains two pneumatic pass-throughs, one BNC passthrough for analog video input, and two high-current Anderson Powerpole connectors. The two Powerpole connectors connect the 48V power supply to the safety circuitry in the TCU and to *Boxfish's* tether. A TCU SID is located in Figure 11.

Tether

Boxfish's reliable, manageable, and lightweight (3.6 kg) tether (Figure 12) is designed to transport necessary signals, power, and pneumatics between the TCU and ROV, and retains many key characteristics from Rovotics' previous designs. The tether is wrapped in a durable, flexible sheathing that protects the lines housed within.

Figure 12. Tether Components

Two American Wire Gauge (AWG) high-performance insulated silicone DC power lines are used to supply 48V power to the ROV. The 12 AWG silicone wire was chosen for its lower weight, compact size, excellent flexibility, and lower resistance in order to minimize the voltage drop and power loss across the tether. The resistance of the power cable is 0.3 ohms, meaning that, at the maximum 30 A current draw, the voltage drop is 30 A * 0.3 ohms = 9V. This gives our ROV a minimum operating voltage of approximately 39V after the tether, which is above the programmable 34V cut-off

voltage of the DC to DC voltage converters. A Category 6 Ethernet (CAT6A) cable is used as a network line to *Boxfish's* Raspberry Pi computer due to its superior signal propagation characteristics compared to CAT5E. One 735a coaxial video cable is used to send analog video information to the TCU. It was chosen due to its immunity to interference and 75-ohm impedance rating, which makes it ideal for carrying National Television System Committee (NTSC) video signals. In order to accommodate *Boxfish's* pneumatic systems, two 1/4 inch pneumatic lines are used. The diameter of the tubing was chosen to balance weight and airflow based on the requirements of the tools developed for the RFP.

Electronics

The electronics system (Figure 14) was designed around the principles of serviceability, low build and lead times, and operational stability.

The Power Systems Enclosure (PSE) (Figure 13) contains two DRQ1250 voltage converters, a custom PCBA, six Electronic Speed Controllers (ESC), and an Arduino Nano. The control signals for the thrusters are sent to the PSE using a simple USB connection to the main Raspberry Pi computer in the MEE. The signal is received by the Arduino Nano which then communicates to the ESCs. The Arduino Nano is programmed with a watchdog timer to default the thrusters to zero thrust in the event that communication to the main Raspberry Pi is disrupted. The PCBA connects the voltage regulators to the rest of the electronics architecture and simplifies
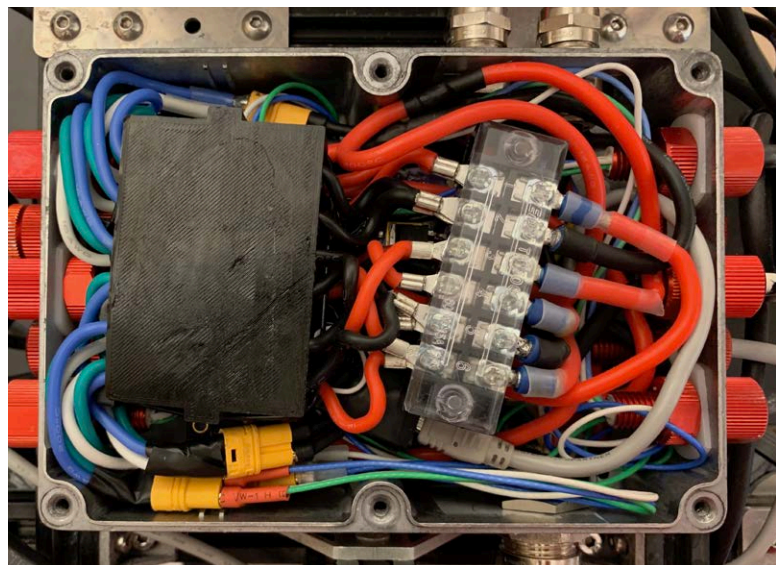

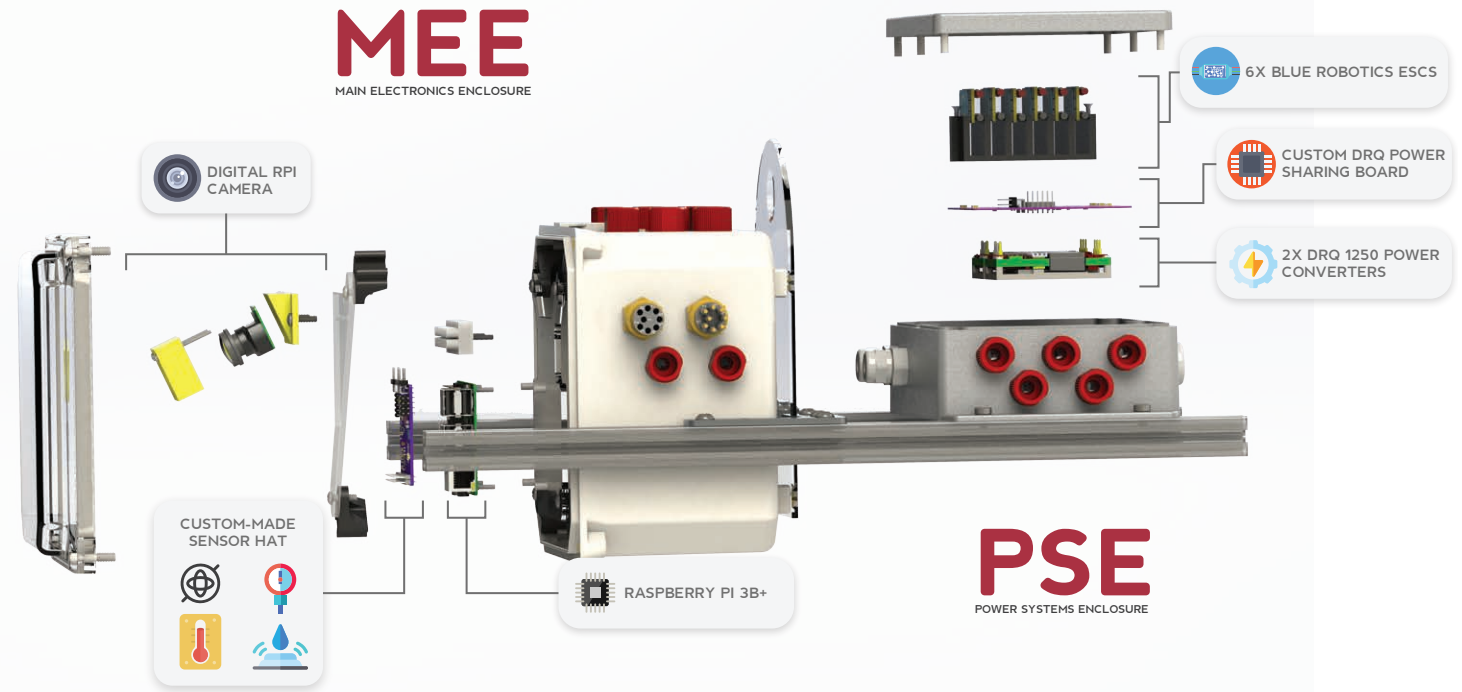*Figure 13. The Power Systems Electronics*

Figure 14. The Electronics Architecture

wiring to create a more modular and serviceable system. The six T100thrusters are connected directly to the PSE via proven Blue Robotics 6 mm penetrators.

The two Murata DRQ1250s convert 48V from the tether to 12V at up to 100A. The DRQ1250s were chosen for their nominal power output range, reliability, and performance characteristics along with their array of safety features including overcurrent, overvoltage, and undervoltage shutdown, and short circuit protection. During our design planning phase, the team considered an alternative regulator solution using golf cart regulators. After testing, design reviews, and cost analysis, it was decided that DRQ regulators would continue to be our regulator of choice. Even with the off-the-shelf waterproofing and low cost, the golf cart converters would have added weight, wiring complexity, and bulk to the ROV.

The DRQs are housed on a power board that was designed and assembled by Rovotics to include a custom power-sharing bridge that allows for supply redundancy to the Main Electronics Enclosure (MEE). The custom bridge allowed Rovotics to save on cost and avoid using limited-availability power-sharing DRQ1250 components.

The MEE (Figure 15) contains *Boxfish's* main computer, a Raspberry Pi 3B+, and a custom design and assembled peripheral and sensor PCBA named ROV Hat (Figure 16). ROV Hat streamlined the wiring and improved system reliability while containing a temperature sensor, humidity sensor, pressure sensor, and a 9-axis Inertial
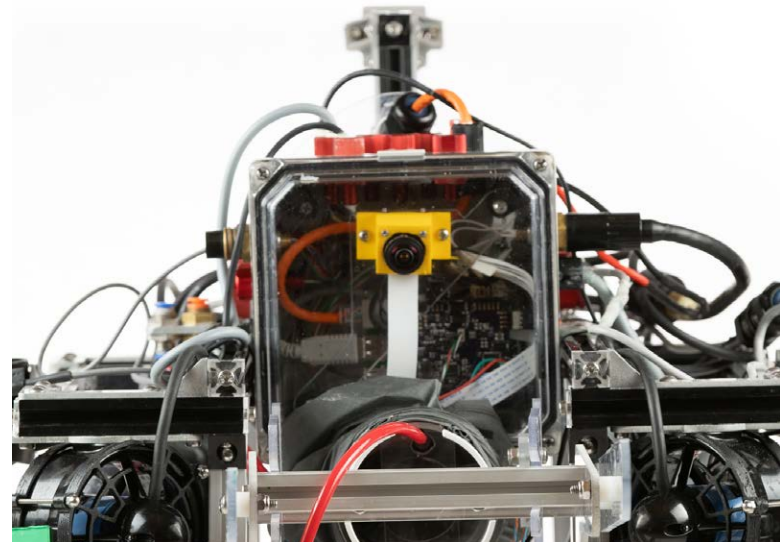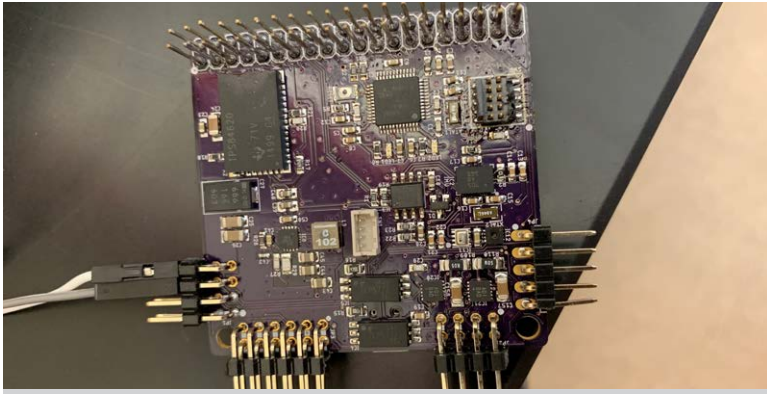

Figure 15. The Main Electronics

Figure 16. Custom Designed and Built ROV Hat

Measurement Unit (IMU) that provide valuable safety and control data to the Raspberry Pi. This sensor data is monitored by safety algorithms and ROV operators.

A digital Raspberry Pi camera is mounted inside the MEE (Figure 17). The camera has a 110° FOV and is connected via Camera System Interface (CSI) to the Raspberry Pi. The Raspberry Pi sends the video stream over the ROS network with under 110 ms of lens to screen latency. The high-quality, low-latency 1280x720 digital video stream is advantageous for software-oriented mission tasks that require high-quality and low-latency digital video. The position of the digital camera also makes it ideal as a general-purpose pilot camera to help orient the pilot when completing mission tasks through the tool-perspective analog cameras.

The analog video system utilizes a custom multiplexer PCBA that is epoxy-potted in a custom tray housed under the top deck of the ROV (Figure 18). The multiplexer was designed to provide a compact form
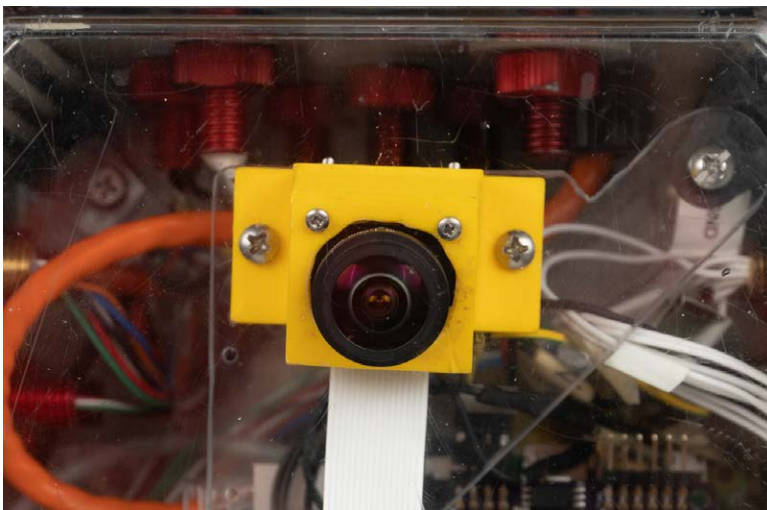

Figure 17. The Raspberry Pi Camera

factor with modular tool-perspective cameras. Bulgin connectors were used at the end of each camera to make them individually removable. The output of the multiplexer board is sent up the tether via the 735a coaxial cable and displayed directly by an analog monitor. The result is a lens to screen latency of around 90 ms. The analog cameras are an inexpensive and reliable system that has been proven in previous Rovotics designs. To see the electronics SID or power budget, reference Figure 19 and 20 respectively.
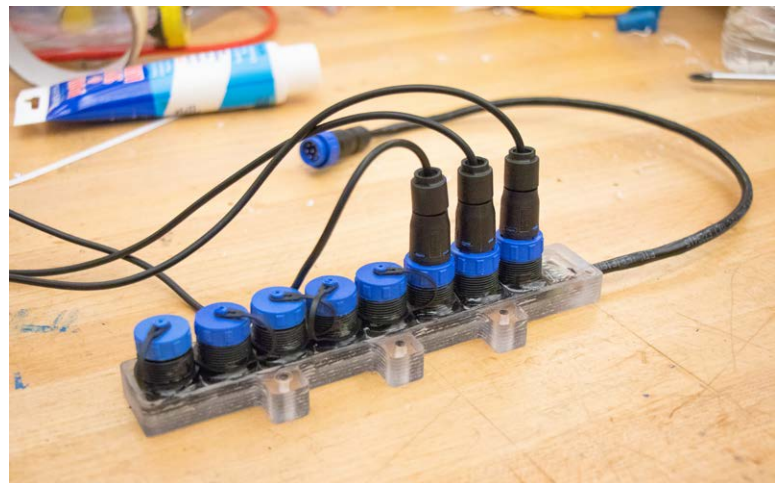

Figure 18. ROV Camera MUX

Submersible Connectors

Boxfish uses a combination of Blue Robotics cable penetrators, SubConn wet-mateable electrical connectors, Bulgin 400 series miniature power connectors, and inexpensive cable glands. To reduce costs, Blue Robotics cable penetrators were used for permanent connections between the MEE, PSE, Camera Mux Enclosure (CME), and thrusters. The tether's power connection utilizes SubConn connectors for their durability and reliability. For data, the tether uses a cable gland due to its low cost, availability, and ability to provide the gigabit ethernet connection that is required for the digital camera system. Bulgin connectors are primarily used to connect the analog cameras to the multiplexer since they are small, lightweight, inexpensive, and easily removable from the epoxy-potted CME. With the added serviceability of the new MEE design, Rovotics can use more reliable Blue Robotics cable penetrators for tools while maintaining modularity. The balance of modularity and reliability helps minimize ROV downtime.
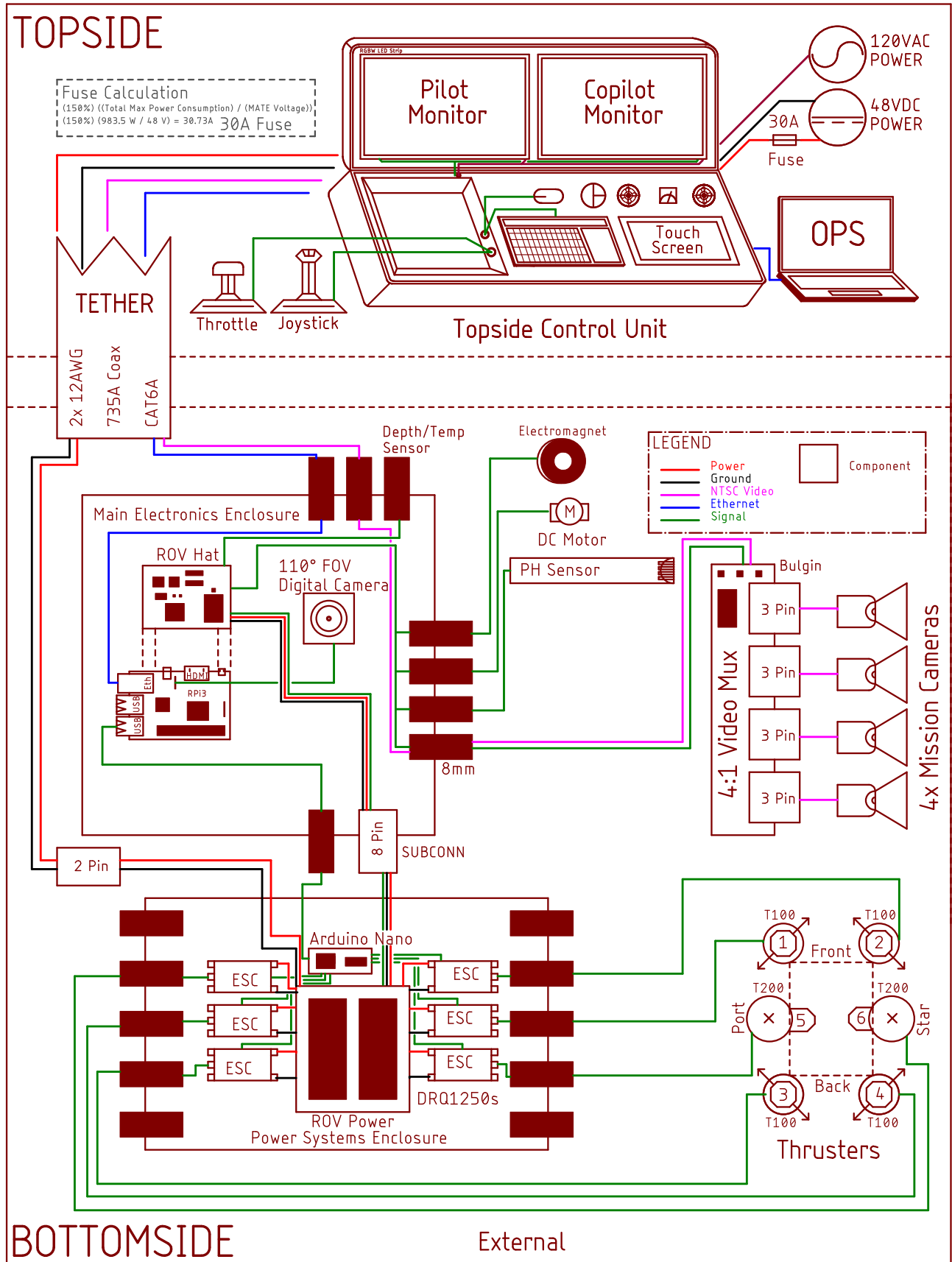
TOPSIDE

Fuse Calculation
(150%) ((Total Max Power Consumption) / (MATE Voltage))
(150%) (983.5 W / 48 V) = 30.73A 30A Fuse

RGBW LED Strip

Pilot Monitor

Copilot Monitor

120VAC POWER

48VDC POWER

30A Fuse

TETHER

2x 12AWG
735A Coax
CAT6A

Throttle   Joystick

Touch Screen

OPS

Topside Control Unit

Depth/Temp Sensor

Electromagnet

DC Motor

PH Sensor

Main Electronics Enclosure

ROV Hat

110° FOV Digital Camera

HDMI
Eth
USB USB
RPi3

8mm

SUBCONN

8 Pin

2 Pin

LEGEND
Power
Ground
NTSC Video
Ethernet
Signal

Component

Bulgin
3 Pin
3 Pin
3 Pin
3 Pin
4:1 Video Mux

4x Mission Cameras

Arduino Nano

ESC
ESC
ESC

ESC
ESC
ESC

DRQ1250s

ROV Power
Power Systems Enclosure

T100 1 Front 2 T100

T200 Port 5 6 Star T200

T100 3 Back 4 T100

Thrusters

BOTTOMSIDE

External

Figure 19. The Electronics SID

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Device	Quantity	Nominal Voltage (V)	Max power (W) per device	Total (W)
T100 Thruster	6	12	130	780
Blue Robotics ESC	6	12	6	36
ROV Hat and Raspberry Pi	1	12	10	10
DRQ1250 Voltage Converter	2	48	19.2	38.4
Cameras	4	3.3	0.5	2
Video Multiplexer	1	12	0.1	0.1
Electromagnet	1	12	10	10
Brushed DC Motor	1	12	6	6
Tether Max Power Loss	1	48	101	101
Total Power Consumption				983.5
Total Aviailable Power at ROV	Total Available Power at Input SubConn = (MATE Power) - (Tether Power Loss) = 1440 W - 101 W = 1170 W			
Fuse Calculations	(150%) ((Total Max Power Consumption) / (MATE Voltage)) = (150%) (983.5 W / 48 V) = 30.73 A			
Fuse Value = 30 A				

Figure 20. The Power Budget

Pneumatics

Boxfish's Cannon Lift Bags and Marker Release mechanisms are pneumatically powered using air regulated on-deck at 2.76 bar (40 psi). The air is sent to the tools through dual 6.35 mm pneumatic lines to the ROV, providing quick inflation of the cannon lift bag and decreased response time of the marker release mechanism.

The main solenoid housed in the TCU acts as a safety valve that is controlled by the software safety algorithms. It can be manually turned on and off through a button on the TCU's touchscreen. The Cannon Lift Bag is controlled using a two-way normally-closed solenoid. The marker release mechanism uses a three-way two-position normally-closed solenoid to allow the spring-return piston to reload between markers. Both of these systems can be controlled using the software GUI.

Reference Figure 21 for the pneumatics SID.

SOFTWARE

Rovotics developed a new software architecture built on the Robot Operating System (ROS). This software architecture's modular system is organized around easily maintained "nodes", such as control interfaces and vector drive algorithms. These nodes are connected over a network, meaning new features can be quickly added with low risk to core ROV systems.

ROS tools streamlined development and decreased development time. For example, Gazebo, an open source simulation software that is integrated with ROS (Figure 22), allowed employees to test algorithms without access to the physical ROV. The shift to ROS allowed for the use of thoroughly-tested, open-source
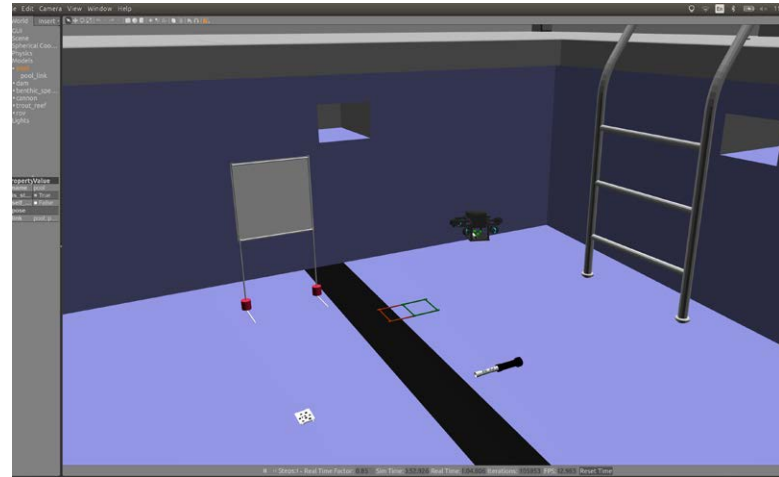

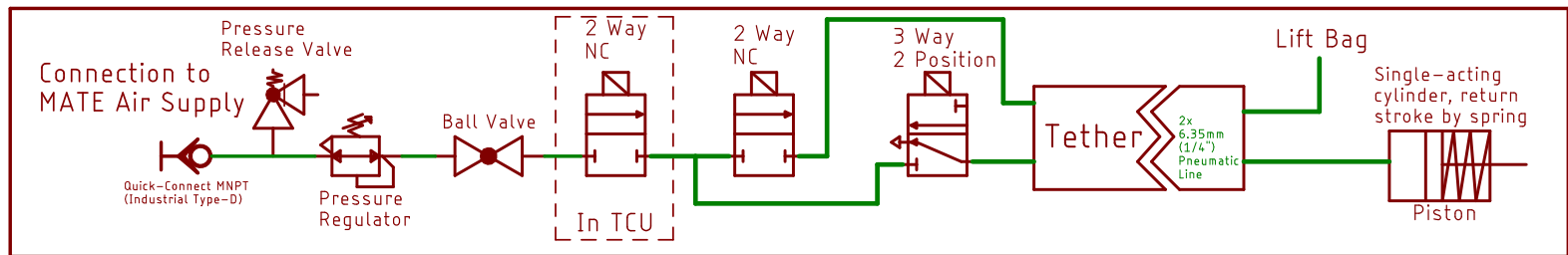Figure 22. ROV Simulator in ROS

Figure 21. Pneumatics SID

code and algorithms to decrease development time and increase the reliability and robustness of the software platform.

The ROS platform is composed of a combination of "publishers" and "subscribers". Each node can publish or subscribe to various data channels to handle ROV functions. Publishers broadcast data over the ROS network while subscribers receive that data and use it to perform various tasks or computations. This publisher and subscriber system makes sending information over the network and between programs simple, making the system modular and maintainable.

Because of the modularity of ROS, additional sensors and features are easy to add, as the nodes operate independently of each other. This modularity also means debugging can be done from any device connected to the network, including an external computer, allowing multiple employees to easily debug software problems on the ROV or testing platform.

A newly-implemented software development process ensures that code is well-documented and tested before integration with the ROV. The process includes
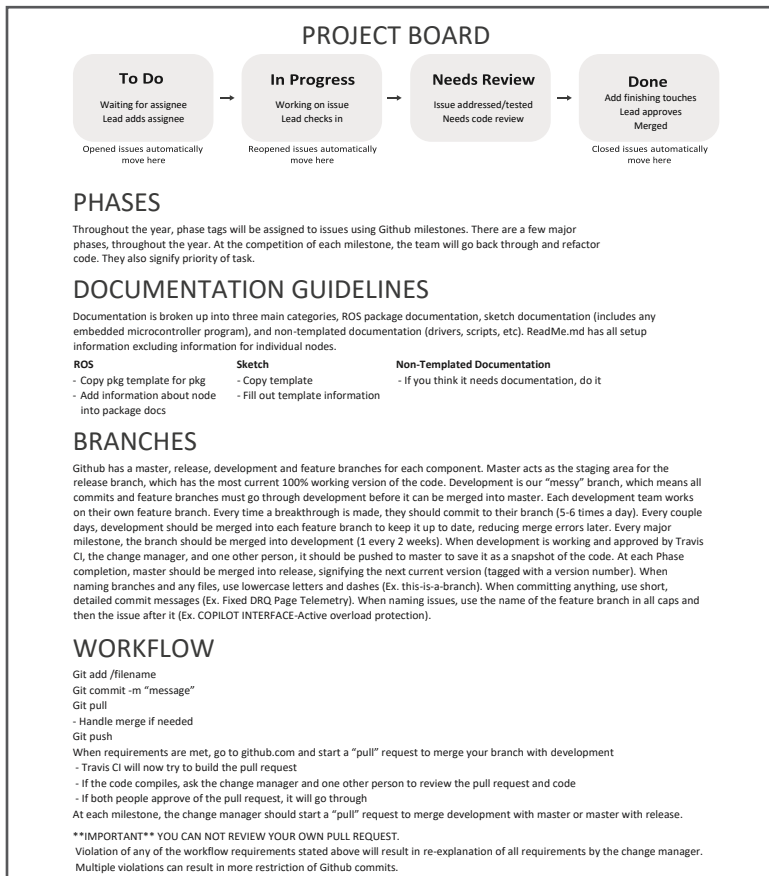

Figure 23. Github Workflow

Travis Continuous Integration (CI) to test code at every step. Each piece of software, written as either a new ROS node or set of nodes, is tested on a software test platform and reviewed using our standardized Github workflow (Figure 23). All of these improvements have minimized ROV downtime resulting from software errors.

Reference Figure 24 for the software flowchart.

Topside

The topside platform consists of a web page GUI for the copilot and operations specialist, the TCU touchscreen, and Robot Operating System (ROS) nodes that run on the Intel NUC. The improved topside GUI features brand-new copilot, sensor, DRQ, and ops webpages (Figure 25). These various GUIs display
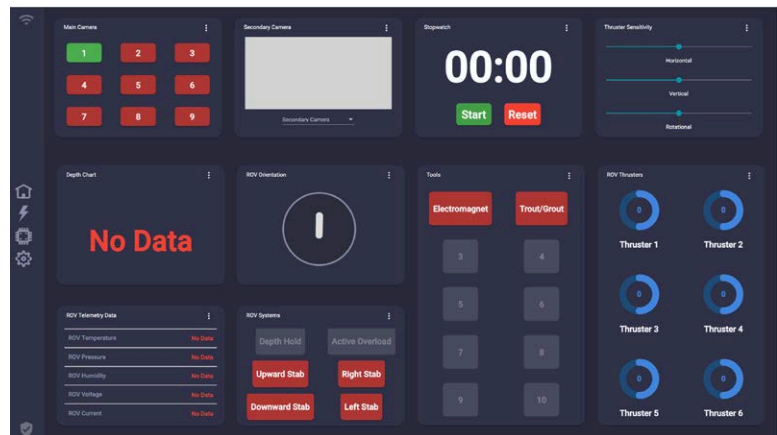

Figure 25. Copiltot GUI

critical ROV information, including sensor data and ROV status, in an intuitive format. On the TCU, the integrated touchscreen allows for control of functions such as power and pneumatics. All of these GUIs are built using the Angular 7 Software Framework in HTML and TypeScript. These webpage GUIs communicate with the ROS network through the open-source library roslibjs. For redundancy and resilience, backup interfaces were made using the ROS parameter system and an RQT graphical interface. The backup topside system ensures that even if the webpage encounters a problem, the deck crew can still control crucial functions of the ROV.

Bottomside

Boxfish's onboard software functions are handled by a Raspberry Pi 3B+, which uses a 1.4 GHz 64-bit quad-core Broadcom ARM Cortex A53-architecture
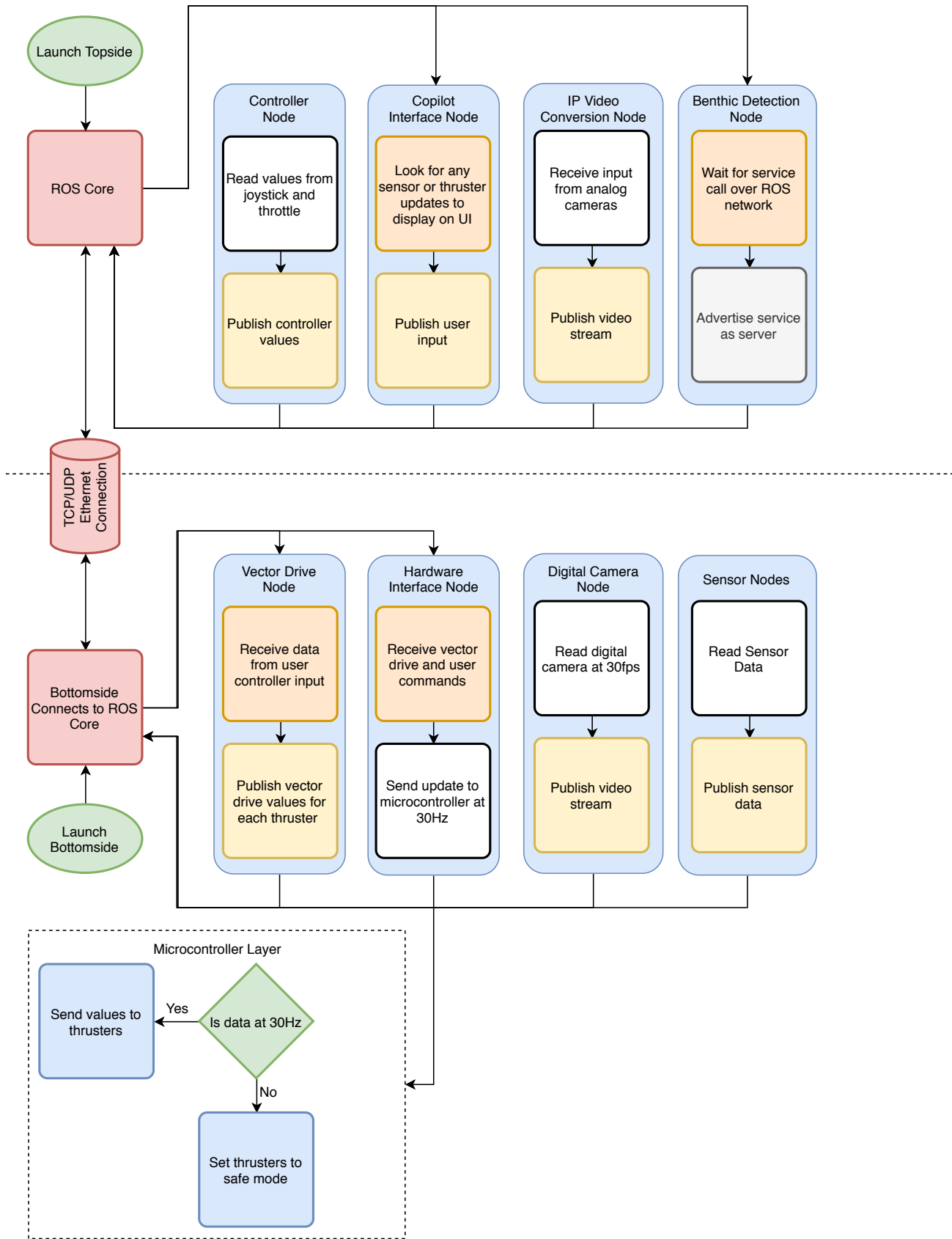
Figure 24. Software Flowchart

processor running Ubuntu MATE 18.04. The Raspberry Pi manages hardware interfaces for ROV functions, such as thrusters and tools. For thruster control, the Raspberry Pi communicates with an Arduino Nano which then communicates with the ESCs to update the thrusters. The Arduino Nano has a watchdog timer to bring the thrusters to neutral in the event of a critical system failure on the Raspberry Pi.

The Raspberry Pi communicates to the onboard ROV sensor hat over the Inter-Integrated Circuit (I2C) bus. Sensor data is read by the bus and transmitted over the ROS network so the information can be accessed by any node on the software architecture, such as the topside GUIs. Additionally, a custom interface written for the DRQ1250 voltage regulators allows for easy data logging and reprogramming of each device. This allows Rovotics to debug power supply issues quickly and adapt the ROV to various load situations.

TOOLS

Hook

The hook (Figure 26) is made out of high-density polyurethane and contains cutouts optimized for picking up and transporting the benthic species rock, old trash rack, and reef ball. It is mounted under the bottom deck of the ROV. This tool is simple yet versatile.
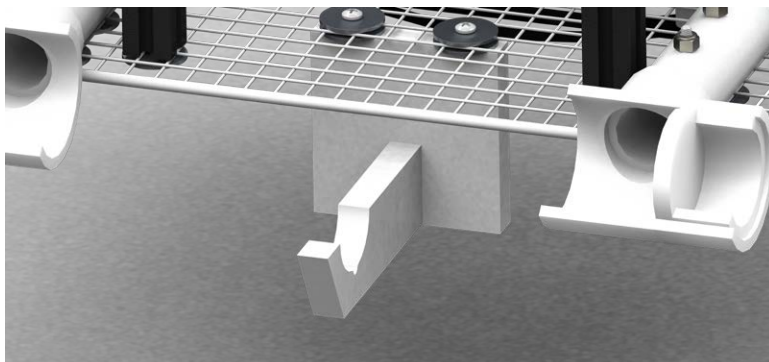

Figure 26. Hook

Cannon Marking

The cannon shell marker release mechanism (Figure 27) uses two racks that each hold up to five .5 inch PVC tees that are either red or black. The tees are stacked vertically, with a flexible mechanism that uses lateral force to release the bottom tee out of the mechanism. When red markers make contact with the metal cannon debris,
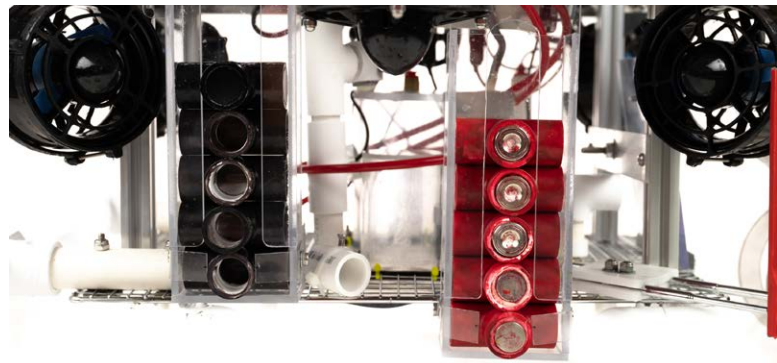

Figure 27. The Cannon Markers

the magnet attaches to the debris and pulls the tee out of the rack. Non-metal debris is marked by the black tees, which are ejected by a 1.9 cm pneumatic piston.

Tire Gripper

Boxfish's tire gripper (Figure 28) uses rubber bands and a scissor hinge to automatically engage and then stay engaged during retrieval. When pushed against the tire, the clamp automatically opens and then slides closed around the tire. Then, the clamp uses the tire's downward force and the rubber bands to remain locked. This tool contains a quick-release button that allows it to be interchanged with the cannon lift bag mechanism.

Figure 28. Tire Grippers

Environment Sensors

Boxfish has a variety of sensors to monitor its external and internal environments. For example, pH (Figure 29) and external temperature sensors monitor the water conditions while sensors mounted on ROV Hat track current ROV status, including internal pressure, temperature, humidity, and orientation. The various GUIs display the data in an easy-to-read format, allowing the
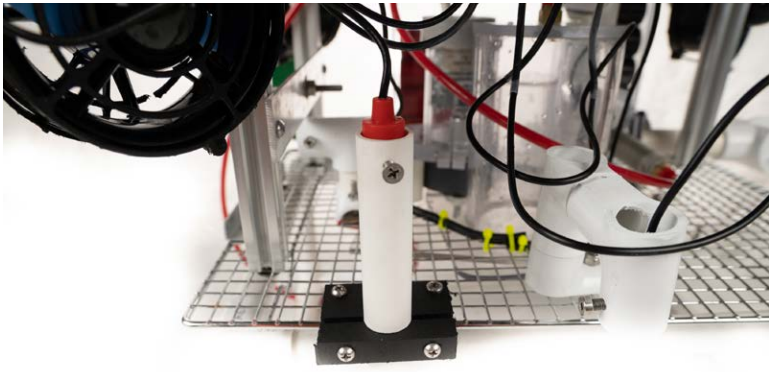
Figure 29. pH Sensor

deck crew to quickly determine ROV and environment status.

Trash Rack

The trash rack tool is designed to hold and install the new trash rack. The tool has customized 1.5 inch PVC cradles which hold the bottom sides of the trash rack and an electromagnet that attaches to the U-bolt (Figure 30). When attached, the trash rack rests in the cradles at a 20° angle from vertical and is held up by an electromagnetic attached to the trash rack's U-bolt. The ROV pilot can disengage the electromagnet to drop the trash rack in place.
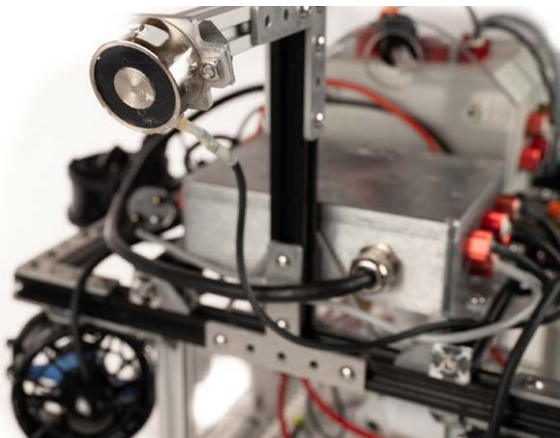

Figure 30. Trash Rack Electromagnet

Cannon Measurement

The cannon measurement system uses a combination of mechanical and software components to measure the length and diameters of the cannon. *Boxfish*

is fitted with a telescoping ruler that is located in direct view of a camera (Figure 31). When the scale is placed next to the cannon, the operations specialist can take a screen capture and use the known size of the ruler to solve for the unknown size of the cannon through pixel ratios.

Figure 31. Cannon Measurement Ruler

Trout/Grout

The trout/grout tool consists of a series of polycarbonate cylinders with a single rotating trap door mounted to the bottom deck of the ROV (Figure 32). The single motor unit is sealed in a polycarbonate tube, with the shaft extending through the bottom and attaching to the trap door. Bushings on both sides of the shaft seals ensure any lateral force falls on the mounting system instead of the motor. The larger storage cylinder holds grout while the smaller cylinder holds the trout fry. A downward-facing tool-perspective camera allows the pilot to accurately place the grout and trout fry.
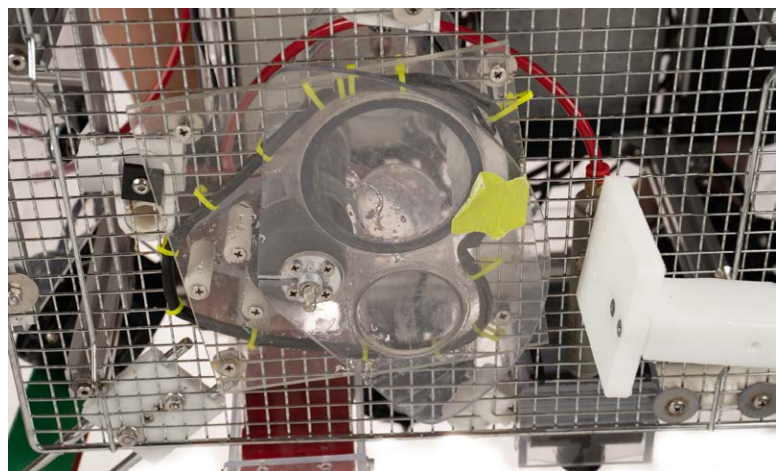

Figure 32. Trout/Grout Holder

Cannon Lift Bag

The cannon lift bag is designed to grab the cannon and then float it to the surface (Figure 33). This tool contains two systems: The gripper/lift bag and the gripper's dock. Once the gripper is placed around the cannon, the air is pumped into the lift bag causing the lever with the lift bag to flip up, which firmly clamps the cannon. Once the volume of air is sufficient, the lift bag and clamping mechanism will automatically disconnect from gripper's dock and float to the surface to be retrieved by an employee. The dock is easily detachable using a quick-release button.
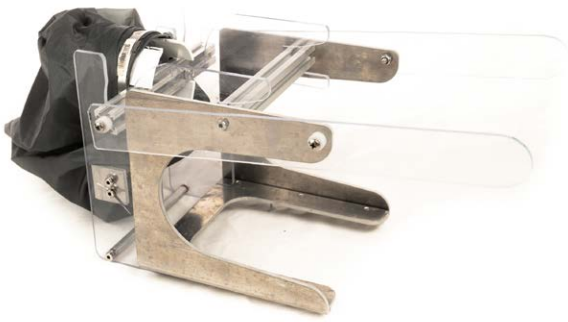

Figure 33. Cannon Liftbag and Dock

Benthic Species

To identify the benthic species, video from a downward facing camera is sent over the ROS network to the benthic species detection node. Via the GUI, the operations specialist takes a screenshot of the benthic species. The screenshot is processed by an algorithm using OpenCV, an open-source image-recognition library. Rovotics used contour approximation to identify edges and vertices. Based on this approximation, the algorithm examines the number of vertices in a given contour to determine the corresponding benthic species. The number and type of each species are then displayed using the software tools GUI (Figure 34) designed in accordance with the specifications outlined in the RFP (DOC-011).

Crack Recognition

To autonomously determine the length of the crack in the dam, Rovotics utilized OpenCV. The crack detection algorithm masks the image from the digital camera for the blue crack and the black marker lines. Once each is identified, the algorithm computes their length in pixels. Using the pixels per centimeter ratio
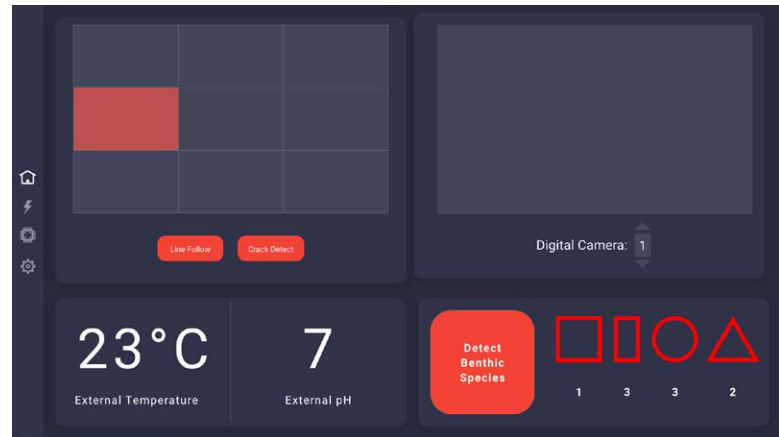

Figure 34. Software Tools GUI

provided by the known length of the black lines, the algorithm can calculate the absolute length of the crack.

Line Following

To autonomously follow the transect line, Rovotics again utilized OpenCV. To follow the line, the forward-facing digital camera image is masked to filter out everything except for the red line. The algorithm computes a motion vector based on the location of the line in the image and the previous direction of motion in order to keep the ROV centered on the line in either the horizontal or vertical axis. Initially, the algorithm was developed and tested using a Gazebo ROV simulation (Figure 35). Once the algorithm proved reliable in the simulation, it was tested and refined in the pool.
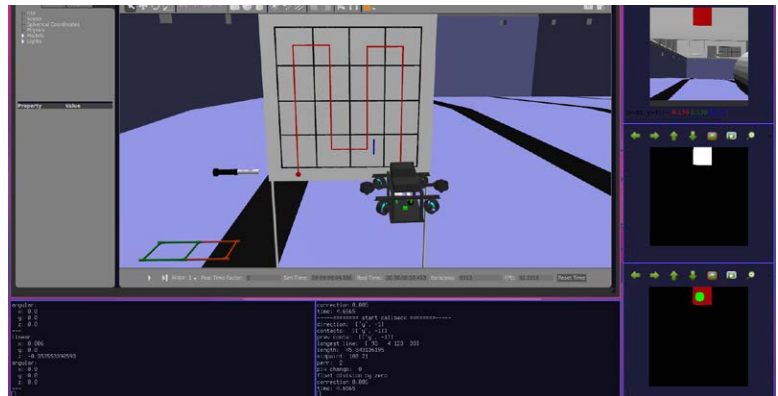

Figure 35. Line Following Testing in Simulator

TROUBLESHOOTING AND TESTING TECHNIQUES

Rovotics began the troubleshooting process by identifying and isolating the problem through Root Cause

Analysis (RCA). Small-scale component tests were run until the problem was located. Company employees then brainstormed various ways to remedy the problem before deciding on a course of action based on factors such as simplicity, cost, and time required.

The ROV was tested in a full-scale "dry run" in which the vehicle was powered and tested in a controlled environment to ensure safety and functionality. The vehicle was then placed into a pool for integration testing to evaluate buoyancy, adjust camera positions, and test the efficacy of particulars tool or functions. A minimum of 30 hours was spent testing the capability of the ROV. Complete missions were run back-to-back by alternating crews for periods of three hours.

For testing hardware, individual components were mocked up prior to the final design. Revisions were made during this time based on prototype performance and testing. For testing software, Rovotics utilized a software test bench (Figure 36) that simulated the electronics, hardware components, and the ROS network to ensure that all software features would work prior to their release and deployment onto the ROV.

Critical integration practices such as the use of a test bench allowed for parallel development and testing. Hardware and software teams were able to minimize ROV downtime through component and integration testing and by enabling fixes to be done without the physical ROV.
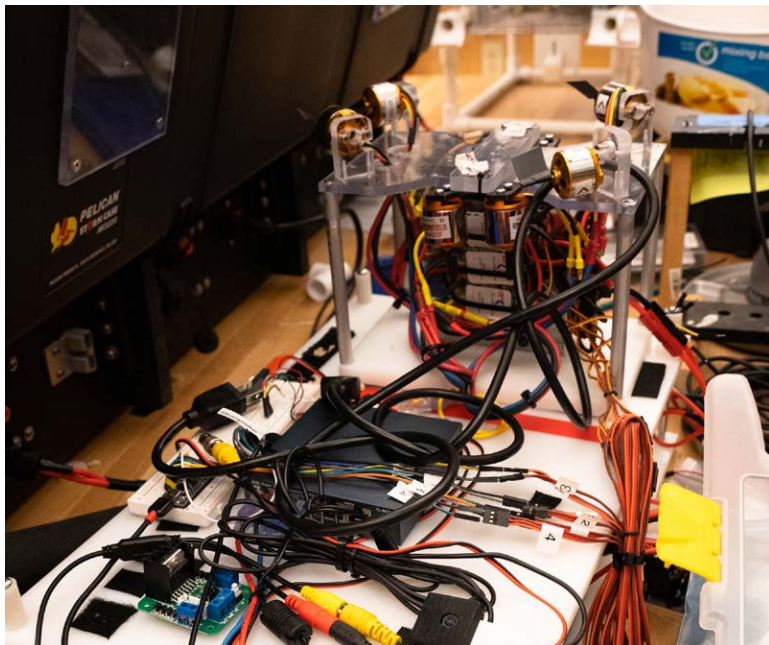
SAFETY

COMPANY SAFETY PHILOSOPHY

Safety is a Rovotics core value. Employees are committed to meeting or exceeding all safety guidelines published by MATE and have a proven track record, consistently passing the MATE safety inspection. Employee safety is the company's highest priority. Rovotics believes that all employees have the right to a safe work environment and that all accidents are preventable. The company's rigorous training, safety procedures, and safety protocols allow employees to avoid accidents preemptively.

LAB PROTOCOLS

To ensure a safe work environment, specific safety protocols are implemented while working in the lab. Rovotics uses Job Safety Analysis (JSA) forms for employees to create and review before performing risky operations. New forms are created whenever a new manufacturing process is introduced. The company's handbook is used to train employees on safety practices such as back safety, electrical safety, hazardous materials handling, housekeeping, and tool safety. Readily accessible Material Safety Data Sheets (MSDS) are available for every product used in Rovotics' production process. Rovotics' lab facility features a chemical vent hood so that electronics soldering can be completed without fume exposure (Figure 37). The work area maintains a negative pressure relative to the room, and fumes are carried up to a roof-mounted vent via ducting.

Figure 36. Software Testbench

Figure 37. Chemical Fume Hood

Figure 38. Employee Training

TRAINING

A peer-to-peer system is used for the safety training of new employees (Figure 38). Newly-hired employees observe veteran employees operating tools and machinery. Veteran employees closely supervise and mentor new employees as they begin to use the equipment. After new employees demonstrate safe and proper operating practices, they can work independently. All employees police each other to ensure that everyone follows established safety protocols. Rovotics continued to use a "Be Smart" tool safety tracking sheet, visible in the lab, that shows who is qualified in using which tools. It is periodically updated as employees learn new skills regarding the safe and efficient use of high-powered tools like the band saw and the CNC machine.

VEHICLE SAFETY FEATURES

At the start of each year, Rovotics reviews MATE safety requirements and maps them to all applicable departments. A safety operational checklist (Appendix 1) ensures that requirements mapped to multiple departments are fully addressed. *Boxfish* has numerous safety features that keep the crew, work environment, and ROV safe during operation. Face O-ring seals and epoxy potting where waterproofing techniques used to ensure all electronics remain dry, protecting personnel and equipment from electrical hazards. A leak detector monitored by the software detects moisture and humidity in the electronics housing. If a leak occurs, the GUI notifies the pilot, and *Boxfish* is shut down The ROV would then be manually pulled to the surface by the deck crew. The

secure strain relief on both the ROV and the TCU ensure the safety of all electrical connectors. The clear lid on the MEE allows for easy visual inspection of electronics.

Thruster guards were mounted to protect debris from entering the thrusters, and frame caps were added to smooth the corners of the top frame.

The TCU incorporates digital displays for the crew to quickly determine if power delivery to the ROV is outside of safe operating values. The software monitors and displays current and voltage information, allowing for quick shutdown in the event of any anomalies. If values outside of safe operating ranges are detected and the software fails to automatically shut down the ROV, a large power switch on the TCU can immediately cut power to the ROV (Figure 39).

Figure 39. TCU Safety Switch

OPERATIONAL AND SAFETY CHECKLISTS

Safety protocols dictated by Rovotics' Operational and Safety Checklists (Appendix 1) are closely followed before, during, and after ROV deployment. Employees also follow operational JSAs for ROV launch, recovery, and waterside safety.

LOGISTICS

SCHEDULED PROJECT MANAGEMENT

Rovotics continued to utilize the PBTR project management process to assist with managing department work assignments and overall project timelines. This year, Rovotics moved over to a digital platform for

its PBTR system. The cloud-based project management software, Trello, was used to keep track of the department tasks and completion dates. Digital cards containing the task, dependencies, assigned employee, and due date were reviewed and maintained across all the departments. The digital system is cleaner and more intuitive than previous post-it note systems and can be accessed on any device anywhere.

Interdepartmental tasks and key deadlines had designated notes on a master Trello schedule (Figure 40), which ensured that all employees were aware
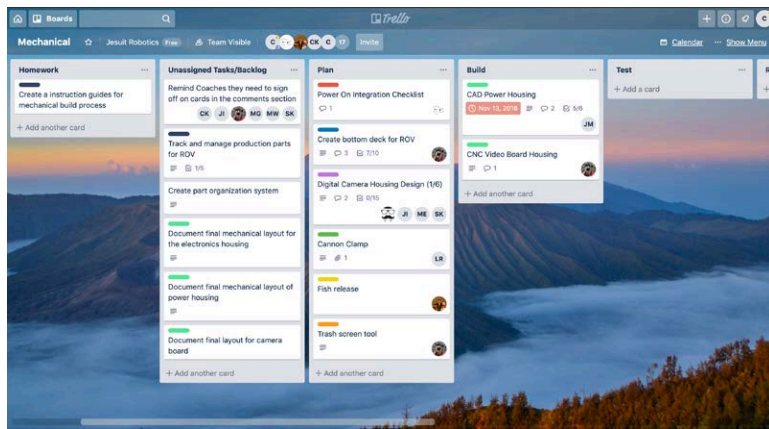

Figure 40. Mechanical Department Trello Board

of upcoming deliverables required by MATE. This allowed the company to manage critical department assignments to ensure overall project expectations. Each workday began and ended with a company-wide meeting where the master schedule was reviewed and the CEO provided updates on the ROV's progress. After the morning meeting, each department met to review their department task board, assign tasks to employees, and discuss individual progress. Between workdays, employees continued work on any daily production goals not met.

COMPANY ORGANIZATION AND ASSIGNMENTS

Rovotics is organized into key departments: Research and Development, Mechanical Design and Manufacturing, Electronics, Software, and Marketing and Publications. To produce the final ROV, documentation, and marketing materials, the departments collaborate through company-wide meetings. Department leads implement MATE deliverables into their department's

task board, assign deliverables to employees, and report progress to the CEO. Key deliverables produced by the departments include the multifunctional gripper developed by Mechanical Design and Manufacturing, custom PCBAs produced by Electronics, the topside GUI developed by Software, and the marketing display produced by Marketing and Publications.

Throughout the development process, senior employees in each department are tasked with training junior employees. Rovotics encourages cross-training to give employees the opportunity to broaden their skills in other departments. By developing knowledge in other areas, employees gain a big-picture perspective, allowing them to provide greater value to the company.

COLLABORATIVE WORKSPACE

To ensure sharing of valuable knowledge and many years of corporate memory, Rovotics uses a widely-available cloud storage system, Google Drive, to manage company files. In addition to providing shared access to company files, Google Drive also assists with streamlining employee work both at or away from the lab. Utilizing Google Apps enables employees to edit files collaboratively and ensures uninterrupted access to the most current version of a document. The shared repository continues to ensure a variety of company topics, including training, past design proposals, and processes, are available to employees.

CODE MANAGEMENT

To ensure efficient parallel code development across multiple software employees, Rovotics utilizes GitHub, a Version Control System (VCS). By using a VCS, Rovotics kept track of overall changes to the software and managed multiple versions. GitHub was selected because it is a well-supported distributed VCS that provides each programmer with a remote and local copy of the code repository. GitHub also enabled software branching and merging which is important when multiple people are working on interdependent files. Should problems arise, GitHub allows restoration of previous versions.

Rovotics' GitHub process was improved to ensure a seamless development pipeline that minimized ROV downtime. Rovotics utilized GitHub tools such as GitHub Issues (Figure 41) and GitHub Project Boards to manage low-level development tasks and software bugs, while high-level software goals were managed on Trello boards.
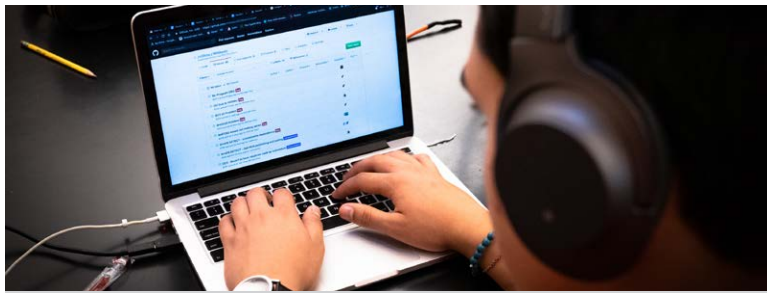
Figure 41. Github Issues Tracker

With the project boards, the software team could easily visualize which "phase" *Boxfish* was on and which "phase" was under development.

The overall source control and versioning process was managed by the software lead. Software employees were held accountable for detailed commit messages during development to efficiently inform other department employees about changes made to the code.

Each commit was then tested with Travis CI to ensure that code was buildable and dependencies were up to date.

BUDGET AND PROJECT AND COSTING

At the beginning of each season, Rovotics prepares a budget with estimated expenses based on the prior year's actual expenses. Employee transportation and competition meal expenses are estimated but listed separately since Rovotics employees pay for these individually. This year, the company budgeted for the purchase of Research and Development hardware, such as an Intel RealSense stereoscopic camera, and a software training program through Robot Ignite Academy.

Income was estimated based on funding from Jesuit High School, donations, and employee dues. To ensure effective use of a limited budget, all purchases

Income	Budget	Type	Production & Operations Budget & Cost Analysis	Project Cost	Difference
Jesuit School Funding	$ 14,450.00	Income	Available Income	$ 22,775.00	
Student Fund Raising	$ 2,800.00	Income	Total Budget		$ 19,977.41
Donations	$ 1,350.00	Income	Production ROV Costs	$ 8,244.73	$ 1,386.68
MATE Competition Awards	$ 350.00	Income	Research & Development Costs*	$ 1,119.09	$ 705.91
Employee Dues	$ 3,825.00	Income	Operations Costs*	$ 6,652.15	$ (1,131.15)
Total Income	**$ 22,775.00**		Capital Costs	$ 2,500.00	$ 380.39
			* Budget overage due to Lodging		$ (1,144.00)
			Funds available for next season	$ 4,259.03	
Production Expenses	**Budget**	**Type**	**Description**	**Project Cost**	**Difference**
Frame & Housing	$ 660.00	Purchased	Polycase Housings, Bottom Deck, aluminum bar	$ 277.83	$ 382.17
Thrusters	$ 1,400.00	Purchased	(6) T100 Blue Robotics thrusters & ESCs	$ 1,036.80	$ 363.20
TCU	$ 542.41	Re-used	Case, Monitors, Electronics, Pneumatics	$ 542.41	$ -
Tether & Connectors	$ 400.00	Re-used	Si wire, CAT5e, coax cable, sheathing, connectors	$ 400.00	$ -
Electronics & Connectors	$ 1,500.00	Purchased	PCB Board Fab, components, connectors, cameras	$ 1,516.20	$ (16.20)
Electronics Rework	$ 500.00	Purchased	PCB revisions and components	$ 352.18	$ 147.82
Pneumatics	$ 100.00	Purchased	Valves, fittings, tubing	$ 85.16	$ 14.84
Mission Tools	$ 500.00	Purchased	Gripper, handle turner, lift bags, PH sensor Kit	$ 584.22	$ (84.22)
Mission Control Center	$ 1,529.00	Re-used	Laptop, joystick; (re-used from 2018)	$ 1,529.00	$ -
Mission Control Center	$ 500.00	Purchased	Intel NUC	$ 483.10	$ 16.90
Raw materials	$ 2,000.00	Purchased	Plastics, metals, hardware, 3D filament, consumables	$ 1,437.83	$ 562.17
Production Budget	**$ 9,631.41**		**Total ROV Production Cost**	**$ 8,244.73**	**$ 1,386.68**
R&D Expenses	**Budget**	**Type**	**Description**	**Project Cost**	**Difference**
Digital Camera System	$ 1,200.00	Purchased	Camera system interface video multiplexer, cameras	$ 517.23	$ 682.77
Training	$ 475.00	Purchased	Robot Ignite ROS Training, Solidworks Training	$ 461.70	$ 13.30
SW Build Upgrades	$ 150.00		SW kits for team members	$ 140.16	$ 9.84
R&D Budget	**$ 1,825.00**		**R&D Project Cost**	**$ 1,119.09**	**$ 705.91**
Operations Expenses	**Budget**	**Type**	**Description**	**Project Cost**	**Difference**
Lodging	$ 4,356.00	Purchased	11 hotel rooms for team/2 per room	$ 5,500.00	$ (1,144.00)
Mission Props	$ 300.00	Purchased	MATE mission props, blue tooth module	$ 303.66	$ (3.66)
MATE Entry Fee	$ 350.00	Purchased	MATE entry fee	$ 300.00	$ 50.00
Power Fluid Quiz Fee	$ 15.00	Purchased	MATE power fluid quiz	$ 15.00	$ -
Printing	$ 500.00	Purchased	Report, display, brochure printing	$ 533.49	$ (33.49)
Operations Budget	**$ 5,521.00**		**Operations Project Cost**	**$ 6,652.15**	**$ (1,131.15)**
Capital Expenses	**Budget**	**Type**	**Description**	**Project Cost**	**Difference**
CNC machine	$ 2,500.00	Purchased	CNC Machine	$ 2,454.00	$ 46.00
CNC station	$ 500.00	Purchased	CNC Station	$ 165.61	$ 334.39
Capital Budget	**$ 3,000.00**		**Capital Project Cost**	**$ 2,619.61**	**$ 380.39**
Employee Paid Expenses	**Budget**	**Type**	**Description**	**Project Cost**	**Difference**
Competition Meals	$ 2,720.00	Purchased	Cash collected for competition meals;17 people	$ 2,720.00	$ -
Transportation & hotel subsidy	$ 3,400.00	Purchased	Cash contribution for car rental, gas, & hotel subsidy	$ 3,400.00	$ -
Estimated Employee Fees	**$ 6,120.00**		**Actual Employee Fees**	**$ 6,120.00**	**$ -**

Figure 42. Budget and Project Costing

are submitted as a purchase request form for review and approval by coaches. Receipts are entered into a project costing sheet each month and tracked against the budget. When spending went over-budget this year, a review was conducted to ensure costs could be covered by other budget areas. As a high school-based company, the company's income is limited, and budgeted expenditures must be closely monitored. The 2018-2019 Budget and Project Costing report is shown in Figure 42.

CONCLUSION

CHALLENGES

During the season, Rovotics set project deadlines based off of previous years' experience to ensure product readiness, however, the deadlines would often be overshot because of large project scope, supply chain problems, and school scheduling conflicts (exams, community service, college applications, etc.). These changes often delayed testing and caused further problems as testing was often not thoroughly completed.

Rovotics experienced quality control and testing procedure problems within the software department earlier this year. The lack of thorough testing and a robust Git workflow led to a slowdown in development due to bugs being released to the ROV. This lack of control resulted in a significant slowdown in development, as bugs wouldn't be discovered or addressed until the final phases of software release, where they would then have to be temporarily fixed at the expense of ROV downtime. The software team addressed this issue by redesigning the software development system to keep track of individual software features and their progress. Implementation of Travis CI, defined branch roles, and a release manager led to a drastic reduction in bugs making it onto the release versions.

LESSONS LEARNED AND SKILLS GAINED

The integration of software and hardware systems led to developmental delays. Seemingly simple procedures, such as updating to gigabit ethernet in the ROV, led to cross-department challenges that were difficult to isolate. In the case of gigabit ethernet, Rovotics experienced packet-loss issues that were

hard to categorize as mechanical, electronics, or software problems. These issues required a lot of time and collaboration between departments to solve. To overcome this, Rovotics expanded test bench environments with all ROV components to help catch integration issues before they reached the ROV.

Rovotics experienced challenges in developing complex projects that required interdepartmental input. Designs would be developed and planned through the viewpoint of only a single department. When the team decided to further develop the system and integrate it onto the ROV, many shortcomings of the design would be found by other departments. In order to bring departments together and minimize these problems, Rovotics learned how to run interdepartmental design review meetings that refined proposals from individual departments or members. As a result of this review system, the digital camera system underwent change due to challenges in integration onto the ROV. Design review meetings (Figure 43) with members from all three departments resulted in a design that minimized risk and improved modularity. The end result was a process that satisfied multiple departments and led to a successful digital camera system.

Figure 43. Design Review Meeting

FUTURE IMPROVEMENTS

Rovotics plans on continuing to optimize the handling of the ROV through software offloading of arduous pilot tasks, such as maintaining ROV position. This will allow the pilot and autonomous flight algorithms to execute fine movements with greater precision. ROV stabilization improvements will make it easier for the pilot to navigate in complex environments and efficiently complete tasks. Greater dynamic ROV stability will also make future autonomous navigation algorithms more reliable and efficient. To achieve this goal, Rovotics has spent considerable Research and Development efforts exploring algorithms and hardware options that would be able to provide information about ROV velocity and position with minimal error. As part of this research, Rovotics aimed to utilize stereoscopic vision with Intel RealSense technology (Figure 44) to not only

Figure 44. Intel Realsense Technology

provide velocity and position data but also to assist in autonomous mission and measurement tasks. Due to the complexity of the project and the level of refinement needed for a successful implementation, Rovotics was unable to implement this system into the ROV this year.

Based on lessons learned this year, Rovotics plans to further expand the test bench to include even more of the mechanical design and peripheral components of the ROV. New developments will add more electronics and mechanical components to test even the seemingly trivial integration tasks that have given us trouble this year. The new test bench will include connectors, a tether, and a full camera system. By including these components and

others, Rovotics will be able to catch more integration problems before they get on the ROV.

ACKNOWLEDGMENTS

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APPENDIX

1. OPERATIONS AND SAFETY CHECKLIST

Pre-Power
Area clear (no tripping hazards, items in the way)
Verify power switches on TCU are off
Tether flaked out on the deck
Tether connected to TCU and secured
Tether connected and secured to ROV
Tether strain relief connected to ROV
Electronics housings are sealed
Visual inspection of electronics for damaged wires, loose connections
Lid tight on the electronics housing
Thrusters free from obstructions
Power source connected to TCU
Vacuum test electronics housing (see vacuum test procedure)
Check vacuum port is securely capped

Vacuum Test Procedure
Connect vacuum hand pump to ROV MEE
Pump electronics housing to -35 kpa (vacuum)
Verify electronics chamber holds -35 kpa (vacuum) for 5 minutes
Remove vacuum pump and securely cap vacuum port
Repeat test with PEE

Power-Up
TCU receiving 48 volts nominal
Control computers up and running
Ensure deck crew members are attentive
Call out, "Power On!"
Power on TCU
Call out, "performing thruster test"
Perform thruster test/verify thrusters are working properly (joystick movements correspond with thruster activity)
Verify video feeds
Test accessories

Launch
Call out, "prepare to launch"
Deck crew members handling ROV call out "hands on!"
Launch ROV, maintain hand hold
Wait for a release order

In Water
Check for bubbles

Visually inspect for water leaks
If there are large bubbles, pull to surface immediately
Wait 5 minutes, then check leak detector
Engage thrusters and begin operations

ROV Retrieval
The pilot calls "ROV surfacing"
Deck crew alls "ROV on the surface"
"Hands On", thrusters disabled
Operation Technician (OT) powers down TCU
OT calls out "safe to remove ROV"
After securing the ROV on deck, deck crew calls out "ROV secured on deck"

Leak Detection Protocol
Surface immediately
Power down ROV
Inspect (may require removal of electronics)

Loss of Communication
Cycle power on TCU to reboot ROV
If no communications, power down ROV, retrieve via tether
If communication restored, confirm there are no leaks, resume operations

Pit Maintenance
Verify thrusters are free of foreign objects and spin freely
Visual inspection for any damage
All cables are neatly secured
Verify tether is free of kinks

Verify Pneumatics Pressure Regulator Is Set to 2.75 Bar (40 psi)
Verify all pneumatics lines are properly connected to the air source, TCU, and ROV
Activate the pneumatics system by opening the main valve