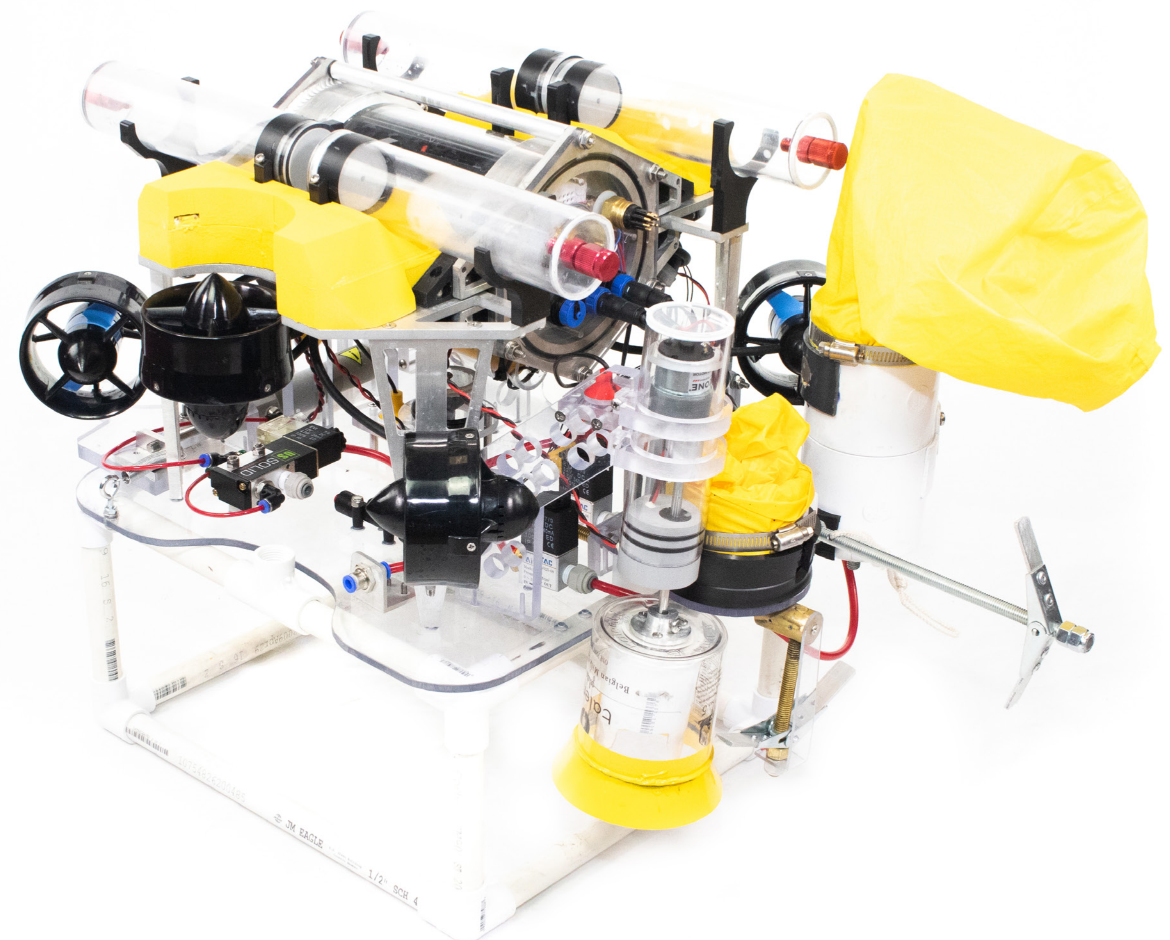

rovotics
underwater solutions

MAKO

JESUIT HIGH SCHOOL
CARMICHAEL, CA
MATE 2018

TEAMMEMBERS

'21 - Alden Parker* - Software
'21 - Andrew Chin* - Electronics
'21 - Avery Gonsalves* - Electronics
'21 - Luke Rosellini* - Mechanical
'21 - Joe Watanabe* - Mechanical
'20 - Jaiveer Gahunia* - Software
'20 - Michael Equi – Electronics/R&D Lead
'20 - Caelin Sutch - Marketing & Publications Lead
'19 - James Whitcomb-Weston - Manufacturing Lead
'19 - James Monroe - Mechanical
'19 - Hayden Kaufman - Electronics Lead
'19 - Adam Graham - Software
'19 - Daniel Brennan - Manufacturing
'19 - Austin Law - CTO
'18 - Sam Paragary - CEO
'18 - Noah Pettinato - Software
'18 - Drake Charamuga – Manufacturing
'18 - Risheek Pingili - Software Lead
Jay Issacs - Head Coach
Steve Kiyama - Assistant Coach

New Members*

I. INTRODUCTION

A. ABSTRACT

Rovotics' newest innovation, *Mako*, is an underwater Remotely Operated Vehicle (ROV) designed to excel in tasks relating to the Pacific Northwest lakes and ocean. *Mako* is fully equipped with tools to locate the wreckage of aircraft, clean up debris, service an earthquake-sensing seismometer, as well as install a tidal turbine and an instrument to monitor the environment. Rovotics (Figure 1), a nineteen-person workforce, 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. A majority of the designs are produced in-house using advanced manufacturing techniques such as precision machining with a Computer Numerical Control (CNC) mill, systematic assembly of custom-printed circuit boards, additive manufacturing with a 3D printer, and other specialized procedures.

Mako is the result of months of planning, research and development, manufacturing, and testing under strict safety protocols. The ROV is designed for serviceability, increased speed, maneuverability, and power efficiency. These features, along with Manual Adjustable Buoyancy Systems (MABS), an advanced flight computer, and Compact Organized Removable Electronics (CORE), make *Mako* our most advanced vehicle yet. This technical document describes the development process and design details that make *Mako* the best ROV for locating vintage airplane wreckage, installing and recovering seismometer equipment, and installing tidal turbine and instrumentation to meet the University of Washington's Request For Proposal (RFP).

Figure 1. Rovotics team members.

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II. DESIGN RATIONALE

A. DESIGN EVOLUTION

At Rovotics, drawing on our corporate memory is an essential part of the design process. *Mako* is the next step in the evolution of Rovotics' product line, and is constructed by drawing on many years of experience building and refining ROVs tailored to meet customers' needs. Analyzing the successes and shortcomings of previous designs allows employees to make significant improvements to the ROV.

This led to the development of ROV CORE and MABS. These innovations allow for the deck crew to quickly change *Mako's* electronics and ballast configurations. We continued to develop new and improved control systems in both electronics and software, shifting from using off-the-shelf control boards to designing and assembling custom control boards.

An additional improvement this year was the continued development of our web server-based control system. Real-time telemetry displays and enhanced pilot, co-pilot, and operations control pages improve pilot control and ROV operations.

The TCU integrates several components into a large, transportable case: pilot and co-pilot monitors, power delivery, controls, and peripheral storage. The consolidation of the different components simplifies set-up times and increases portability.

We also integrated component-level testing (Figure 2) more thoroughly into our design and development process this year. Electronics and software improvements were used first on test vehicles and tabletop test platforms before being implemented in our production ROV. Purchased components, such as thrusters, were tested thoroughly before implementing 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.

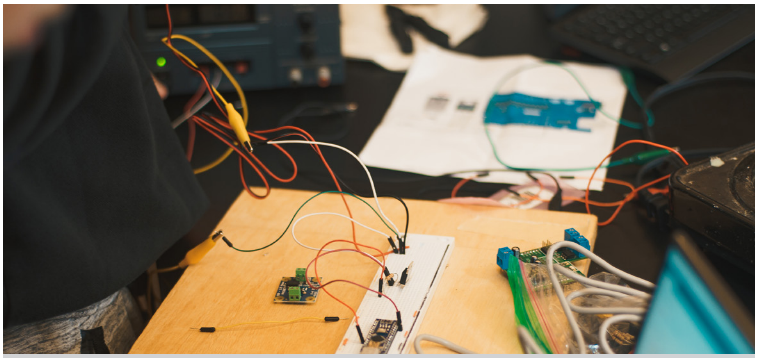


Figure 2. Integration on test platform.

Every manufacturer must consider "make/buy" decisions during the product development process. Components that can be produced in house with available capabilities are generally more economical to "make". Components that require specialized manufacturing processes that exceed Rovotics' manufacturing capability or certain services (such as welding or large scale printing for posters) are sourced commercially. For *Mako* itself, commercially-sourced major components are limited to motor cores, thrusters, speed controllers, servos, cameras, microcontrollers, and similar components.

B. 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 (Figure 3). Concepts were judged based on size, weight, effectiveness,

Figure 3. Initial sketching of Mako's *frame components.*

cost, complexity, ease of manufacturing, safety, serviceability, and reliability, on a decision matrix resulting in designs that were chosen which best fit the RFP requirements. Once each design concept was agreed on, a employee was assigned to oversee development of the component from planning through release. A proof of concept was created using cardboard, foam board, and flexible plastic, after which the entire mechanical design and manufacturing department reconvened to debate the model's viability before the final product was fabricated

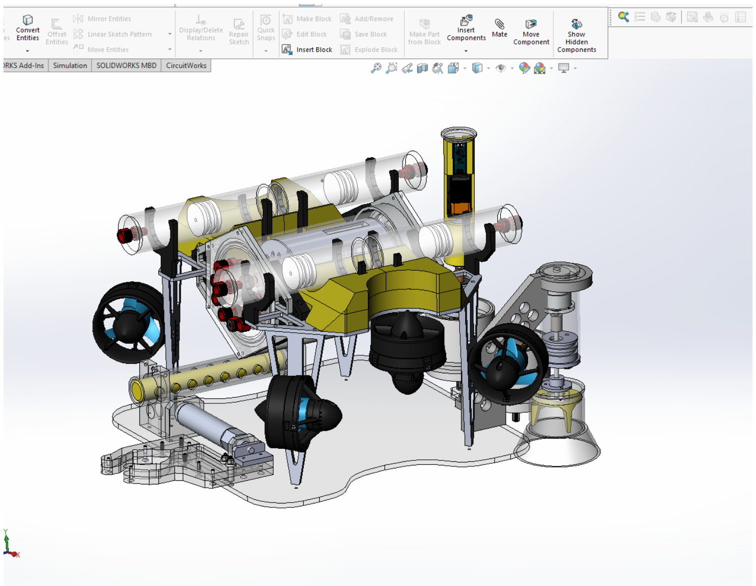


Figure 4. CAD development in Solidworks.

After the concepts are validated, the design department creates 3D models in Computer-Aided Design (CAD) using Draftsight or Solidworks (Figure 4). For parts targeted for production on the CNC mill, the CAD models are converted in a Computer-Aided Manufacturing (CAM) package, SheetCam. Using SheetCam, engineers generate the "G-Code" tool path files from the drawings, which are then loaded into Mach 4, the machine control software. For some custom parts, CAD drawings are printed at 1:1 scale as templates for jigs to be fabricated by hand.

C. MECHANICAL COMPONENTS

Frame

Designed to be lightweight, sturdy, adaptable, and serviceable, *Mako's* frame consists of two decks: the top deck and the tool deck.

The top deck consists of two main assemblies: the electronic housing (a cast acrylic tube capped by aluminum flanges), and an aluminum wing with two polyethylene (HDPE) cradles. The flanges of the electronics housing connect two aluminum wing assemblies through the HDPE cradles, forming a sturdy top deck. Two thrusters are also mounted on the top deck.

The tool deck is constructed from clear polycarbonate for machinability and serviceability. Designed for a flexible tool layout with multiple independent pneumatic valves, tools can be individually maintained and configured.

The decks are connected by four aluminum struts (Figure 5) that are mounted at the corners of the top deck at 45° angles, and are easily separated by four screws on the bottom deck. The vertical struts have a pre-drilled hole pattern that can adjust the vertical placement of thrusters up to 5 cm, allowing for easy alignment of the center of thrust with the center of mass. This design allows for reconfiguration of *Mako's* tools and improved structural strength, serviceability, and up-time.

Figure 5. Mako's *top deck and struts In CAD.*

Electronics Housing

Mako's main electronics are housed in a 13 cm diameter by 23 cm long clear acrylic tube with an internal volume of 2,859 cm^3, a reduction of 3,173 cm^3 from the previous model. The tube is sealed with custom-machined aluminum flanges at each end. The flange has been redesigned to seal the tube on the outside, rather than on the inside as implemented in previous ROVs. This allows for seamless integration of the ROV CORE electronics system by allowing the plastic electronics casing to easily slide in and out of the acrylic tube (Figure 6). Previously, electronics would get caught on the inside seal while being pulled out. The double O-ring design (inside seal) has also been replaced by a solid Epoxy seal (outside seal). Aluminum was used for the flanges while 6.35 mm (0.25 in) polycarbonate was used for the faceplate because of its machinability, light weight, and strength. An O-ring face seal is used to seal the faceplate to the flange.

The housing's cylindrical shape allows the ROV to be easily waterproofed. Additionally, the clear acrylic allows for easy visual inspection of electronic components and the RGB LED status lights that are built into the ROV CORE architecture as part of the prelaunch safety checklist and post-operation structural inspection. In addition to keeping the electronics dry, safe, and serviceable, the housing assembly is an integral component of *Mako's* frame and the buoyancy system, as described in the buoyancy section.

Two SubConn Micro Circular connectors allow the tether's power, communications, and video to connect through the front faceplate, while waterproofed Bulgin connectors connect the electronics to the tools and the camera system. The rear faceplate contains Blue Robotics penetrators that connect thrusters, external sensors, and

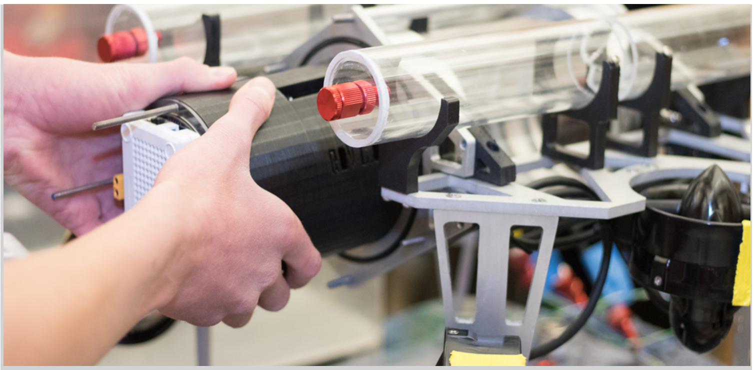


Figure 6. Installing ROV CORE into Mako's *electronics housing.*

a vacuum test plug for pre-operation seal testing to verify hull integrity. The faceplate mount design can be easily disassembled, allowing full access to the electronics system by removing six nuts on each end of the acrylic tube.

The ROV CORE module contains a compact 3D-printed casing to provide protection and reinforcement to the circular circuit boards (Figure 7). This module easily slides in and out of the electronics housing. The casing was designed to be taken apart in specific pieces by unscrewing the backplane connector or the front cap in order to access necessary parts of the electronics architecture for service

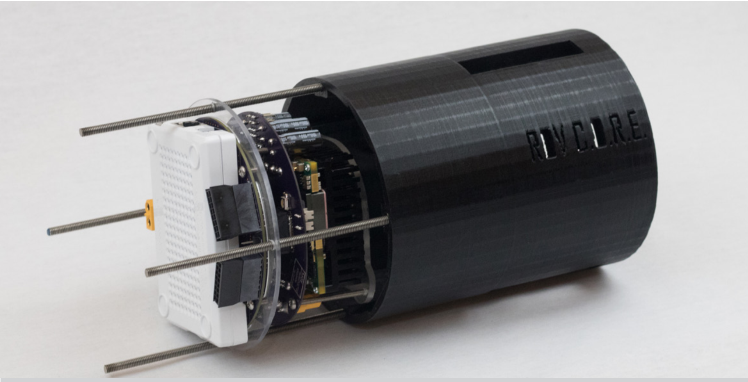


Figure 7. Mako's *ROV CORE module.*

or inspection. The electronics connect to the Blue Robotics penetrators through a custom low-friction backplane connector so that the electronics can be easily removed from the tube along with the removal of the front faceplate.

Thrusters

Mako is equipped with four T100[1] and two T200[2] 12V Blue Robotics thrusters (Figure 8). The T100 thrusters were chosen for their weight,

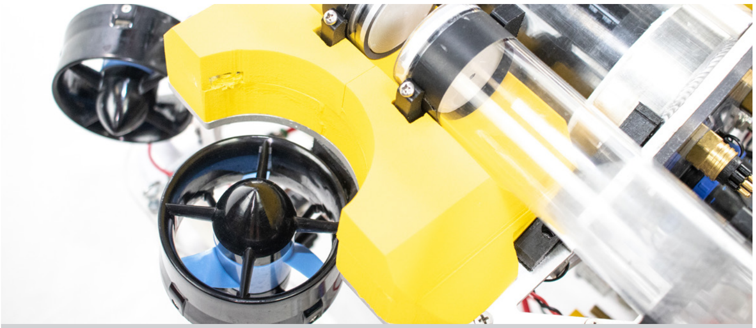


Figure 8. T200 thrusters and MABS mounted on Mako.

affordability, and reliability that has been proven on previous Rovotics' designs. Last year's design, *Lazarus*, used 6 T100 Blue Robotics thrusters which produced undesirable dive and surface times. As a result, the two vertical-facing T100 thrusters were replaced in the *Mako* design with two T200 thrusters. This design evolution has proven to improve the power efficiency and vertical traveling speed. Rovotics tested the T200 thrusters in-house and have found them to have a 33.5% increase in maximum efficiency and a 40.6% increase in maximum thrust when compared to a T100. While the T200s are heavier than the T100s they are still within the weight budget for *Mako*. To achieve stable vector control, 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 accessories in the center of the vehicle. The T100 and T200 thrusters operate at a maximum power of 150W and 192W respectively, well within *Mako's* power budget (Appendix B).

For the safety of personnel and equipment, enhanced thruster guards are mounted on both sides of the thrusters' kort nozzles to prevent fingers, cabling, and foreign objects from getting sucked into the thrusters.

Buoyancy

By applying Archimedes' Principle[5], the mechanical design department determined that *Mako*, along with its components and tether, has a maximum displacement of 13,500 cm^3. It has two main buoyancy components: electronics housing and MABS. At over 2,859 cm^3, the electronics housing is *Mako's* largest displacement component and serves as the main buoyancy device. The smaller displacement of the electronics housing compared to previous years allowed Rovotics to design MABS.

Rovotics created two different MABS: adjustable buoyancy tubes and adjustable foam buoyancy (Figure 8). The four adjustable buoyancy tubes, which can adjust up to a total of 1,639 cm^3 through the use of an adjustable piston that slides through the tube, changing the amount of water displaced, allows the deck crew to adjust *Mako's* buoyancy as needed. The two adjustable syntactic buoyancy foams can displace up to 2,184 cm^3 of water by adding or subtracting subsections. Because of the additional buoyancy allocated to MABS, *Mako* is more flexible in its weight load and balance, making it less reliant on having an evenly-distributed tool load. The total amount of water displaced by MABS is 3,820 cm^3.

A spreadsheet was made to record the displacements and densities of each part of the ROV (Figure 9). This data was used in calculating *Mako's* weight in both air and water. Once the majority of the ROV was manufactured and assembled, the actual and calculated values were compared.

Mako's tether achieves neutral buoyancy by using aluminum air chambers attached 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.

	QTY	Part #	Part	Displacment (in^3)	Weight Outside of Water (lbs)	Total Weight Outside of Water	Total Weight Inside of Water (lbs)	
	2	CFLA811	Cradle Flange	6.17	0.6	1.2	-0.75576	
	1	LTUA805	Electronics Tube	176.71	1.46	1.46	4.90156	
	2	FFBA801	Flange Face Back	7.28	0.32	0.64	-0.11584	
	4	LFAA811	Left Flange Adapter	2.01	0.07	0.28	0.00944	
	2	TFLA812	Top Frame Left	3.97	0.39	0.78	-0.49416	
	4	VPOA811	Vertical Post	3.65	0.36	1.44	-0.9144	
	4	TUBA808	Bouyency Tube	25.13	0.28	1.12	2.49872	
	2	FRIA801	Foam Right	66.65	0.36	0.72	4.0788	
	4	THFA812	Tube Holder Foam	0.7	0.02	0.08	0.0208	
	4	OTHA811	Outer Tube Holder	0.58	0.02	0.08	0.00352	
	6	T200 Thruster	T200	11.89	0.78	4.68	-2.11176	
				Inches displaced of water		Total Dry weight (Weight limit 37.5 lbs)	Ballast Weight in LBS (Want to be slightly negetive)	Ideal Ballast Weight in LBS With Bouyancy(Want to be 0)
Total:	35			304.74		12.48	7.12092	5.87092

Figure 9. Mako's weight budget.

Figure 10. Rovotics TCU.

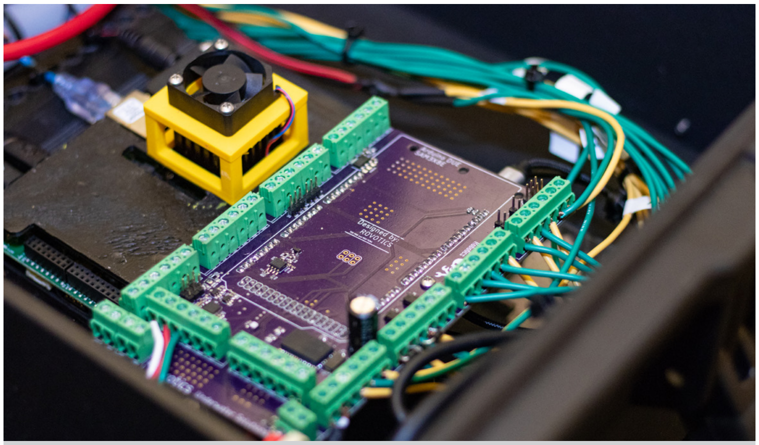


Figure 11. Rovotics TCU custom PCBA.

D. ELECTRICAL SYSTEMS

Topside Control Unit (TCU)

In order to compete with rapidly advancing topside system designs, Rovotics has completely redesigned the TCU into a single case optimized for minimal setup and take down times, as well as peripheral storage (Figure 10). The new TCU contains all the necessary components other than the tether and the ROV.

The TCU 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 UDOO X86, a powerful Single-Board Computer (SBC), housed in the bottom compartment. The monitors and UDOO X86 allow for more advanced heads-up displays and graphics. A 25.6 cm touch screen was installed into the bottom of the TCU for easy 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, allowing for smart software controls and safety features. A Blue Sea Systems power switch has also been implemented as a safety feature to easily 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 internal UDOO X86 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) IP communication. Both the router and ethernet switch are contained within the TCU. The keyboard, mouse, joystick, and throttle connect to the UDOO X86 through a USB hub stored in the TCU.

A custom Printed Circuit Board Assembly (PCBA) streamlined the wiring and has allowed for easier serviceability and expandability through screw terminal connections (Figure 11). 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/humidity sensor and a current sensor send data to the Arduino DUE. To decrease the topside load on the power budget (Appendix B) and to allow for the UDOO X86 and router to be booted without an external power supply, Rovotics has decided to introduce 120V AC into 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 a designated AC housing, for a full Systems Interconnect Diagram (SID), see Figure 12 on the next page.

The back of the TCU contains two pneumatic passthroughs and one Bayonet-Neill Concelman (BNC) passthrough that serves as analog video input. Additionally, high-current Anderson Powerpole connectors are used as connection points for both the input and output 48V supply.

Tether

Mako's reliable, manageable, and lightweight (4 kg) tether is designed to transport the necessary signals, power,

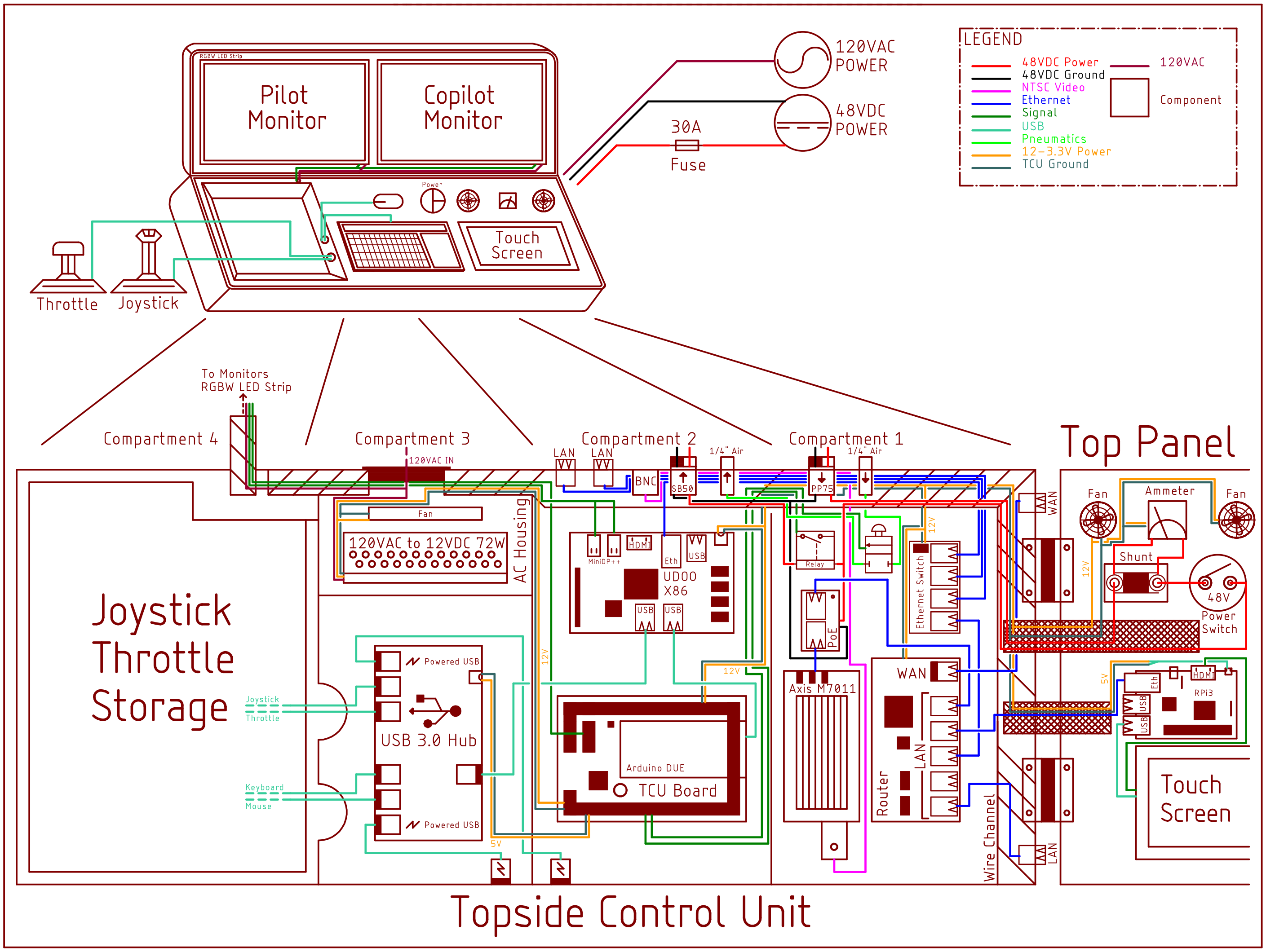


Figure 12. Rovotics' TCU SID.

and pneumatics from the TCU to the ROV while retaining many key characteristics from Rovotics' previous designs. The majority of the tether was reused from last year in order to save on development time and cost.

The tether contains one Category 5 Ethernet (Cat5e) cable, 2/12 American Wire Gauge (AWG) high performance silicone-insulated DC power lines, and a 735A coaxial video cable (Figure 13). The Cat5e carries data via the UDP to and from the ROV and the TCU. Cat5e was chosen over alternatives such as coaxial, Cat4, or Cat6a cables based on its ability to resist interference, cost, and flexibility. All Ethernet terminations use the T568B standard for Cat5e cables. The 735A coaxial video cables were chosen for resistance to interference, small diameter, and 75 ohm impedance for camera compatibility. The power lines are a sufficient gauge to

Figure 13. Rovotics tether containing 2/12 AWG power lines, an Ethernet line, pneumatic line, and a coax cable.

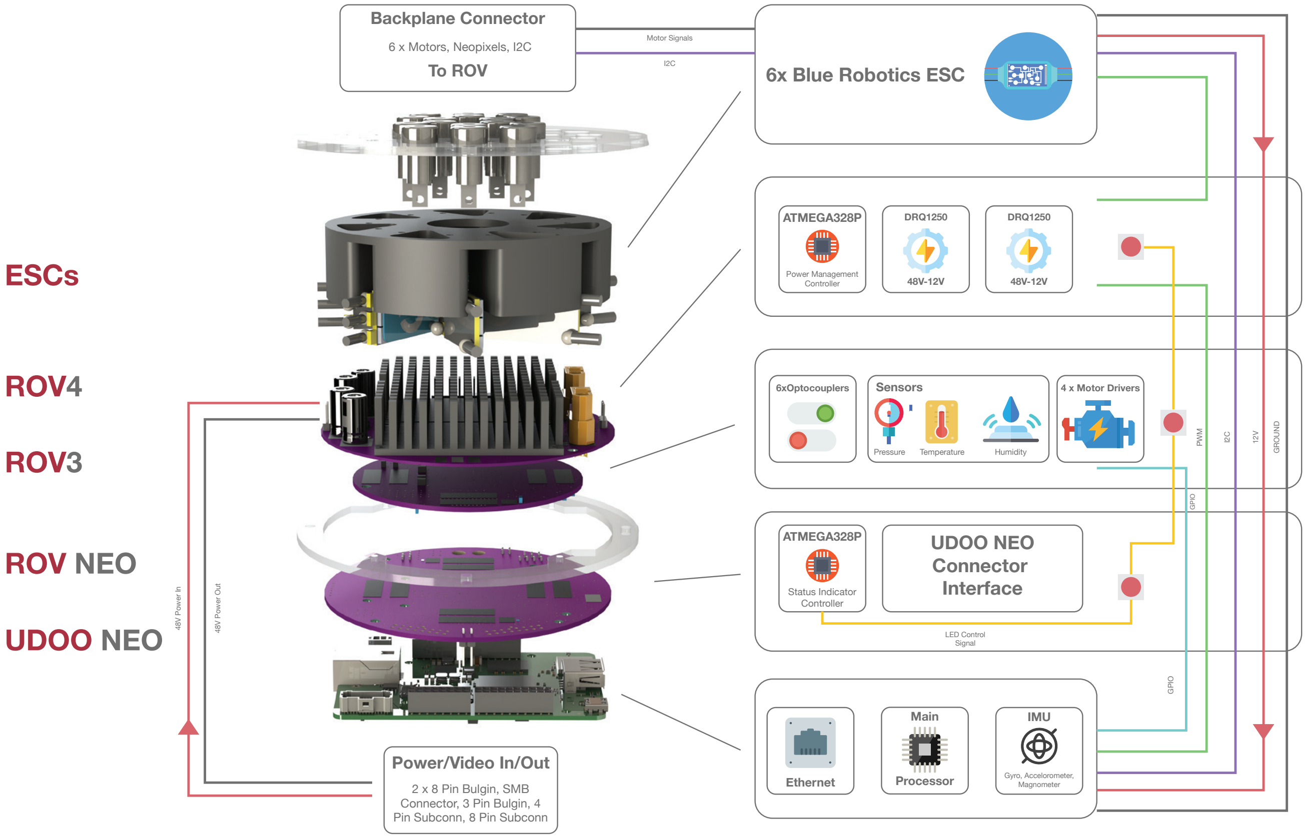


Figure 14. ROV CORE architecture diagram.

minimize voltage drop over the 20 m tether while maintaining flexibility. The power cable is sized for the maximum fuse-limited current draw of 30 A. The power cable has a tested resistance of 0.3 ohms with a maximum voltage drop of 30 A * 0.3 ohms = 9 V. This gives *Mako* a minimum operating voltage at the ROV of approximately 39 V, which is above the programmable 34 V cut-off voltage of the DC-DC voltage converters.

Electronics

Mako's electronics architecture, ROV CORE, (Figure 14) was developed with a completely new design philosophy focusing on a Compact, Organized, and Removable Electronics (CORE) system while also providing superior performance, reliability, and modularity. By advancing PCBA development techniques, Rovotics' custom circular PCBAs (Figure 15) allowed for a drastic decrease in electronic housing size and for an improvement in reliability. The architecture also utilizes readily-available commercial components such as six Blue Robotics Electronic Speed Controllers (ESC's), two Blue Robotics T200 thrusters, four Blue Robotics T100 thrusters, eight National Television Standard Committee (NTSC) cameras, and an UDOO NEO Single-Board Computer (SBC). Using some commercially-available components decreased the necessary development time and allowed for easy testing of the software system.

ROV CORE consists of an UDOO NEO and three circular PCBAs: ROV NEO, ROV3, and ROV4 . The UDOO

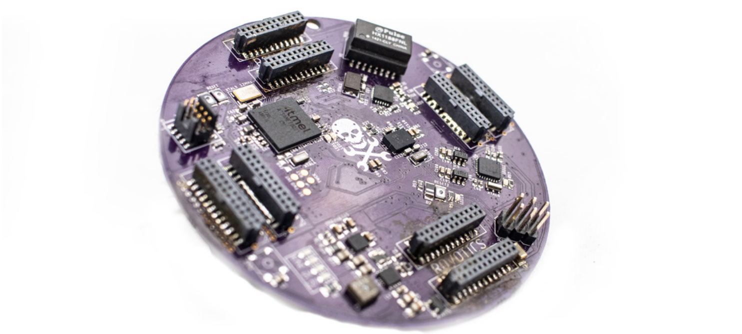


Figure 15. ROV CORE circuit board.

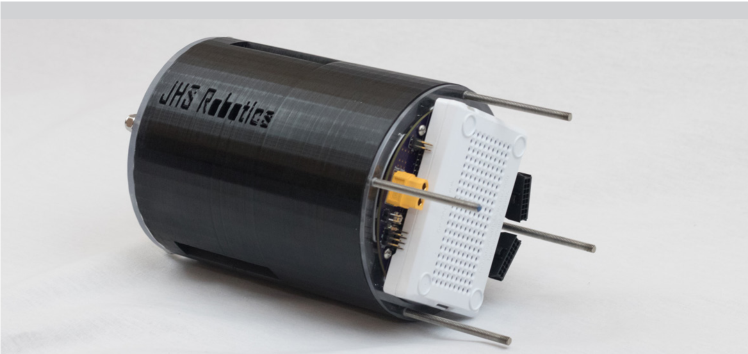


Figure 16. UDOO NEO connected to ROV NEO on ROV CORE.

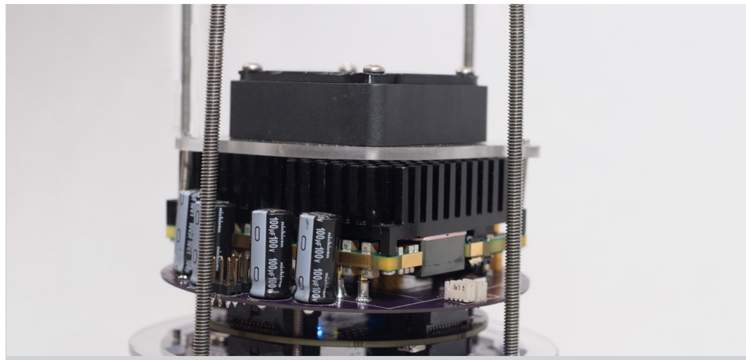


Figure 17. ROV4 Power Management Board with ROV CORE.

NEO connects to the ROV CORE through the ROV NEO circuit board by utilizing a shield type connection (Figure 16). The UDOO NEO contains an accelerometer, magnetometer, and gyroscope for a total of 9-axis of inertial measurement data that allows for precise Proportions Integral Derivative (PID) control algorithms to be run directly on bottomside.

The UDOO NEO was also chosen over the Raspberry Pi because its processor has both a Linux and an Arduino ARM core on the same chip. The Linux and ARM processor cores communicate through a shared-memory messaging protocol that has demonstrated improved reliability over the previously used hardware Universal Asynchronous Receiver and Transmitter (UART) communication systems. The heterogeneous core architecture allowed for a more integrated control of *Mako* by utilizing the abundant peripheral selection of the Arduino based ARM processor while maintaining the performance and software flexibility of a dual core Linux system. The Arduino core is responsible for communicating with the Power Management Controller (PMC) on ROV4 and the six thrusters while the Linux cores are responsible for communicating to topside through UDP IP communication, controlling the motor drivers and switches, and reading both the sensor and wifi based Ocean Bottom Seismometer (OBS) data collected by *Mako*.

Along with the UDOO NEO, ROV NEO contains a dedicated ATMEGA 328P microcontroller which is responsible for controlling the RGB LED user-communication system which displays system boot information, connection status, and safety status to the deck crew.

ROV3 is the sensor and peripheral controller that contains six 12V solid-state switches, four 12V bidirectional DC motor drivers, an internal pressure/temperature sensor, and an internal humidity/temperature sensor. ROV3 was designed to be a cost-effective and highly-expansive 2-layer 76mm diameter PCBA that could be easily upgraded and changed in order to accommodate future hardware or sensor systems.

ROV4 is a custom power distribution and management board that features dual 600W Murata DRQ1250 DC-DC switching voltage converter modules[4] (Figure 17) that were chosen for their proven reliability from past years. Optimal output voltage, output power, compact size, efficiency, onboard conversion monitoring, and built-in protection features were key factors in the selection of the voltage converter. The modules mate with the custom power board using pin receptacles, which allows them to be easily replaced if the converters are damaged. The converters also include additional safety circuitry to prevent catastrophic power failures and allow for *Mako* to continue to convert power in the event of a single module failure. The power board's onboard PMC provides status data to the UDOO NEO SBC for power conversion monitoring. For a complete electronics SID see figure 18 on the following page

The ROV CORE electronics connect to the external video multiplexer PCBA (Figure 19) through

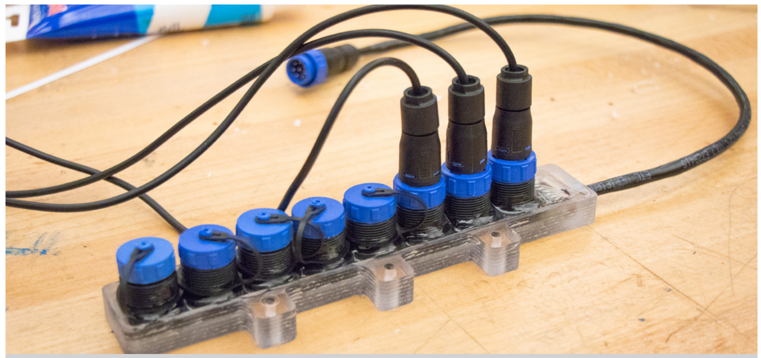


Figure 19. Potted video multiplexer PCBA.

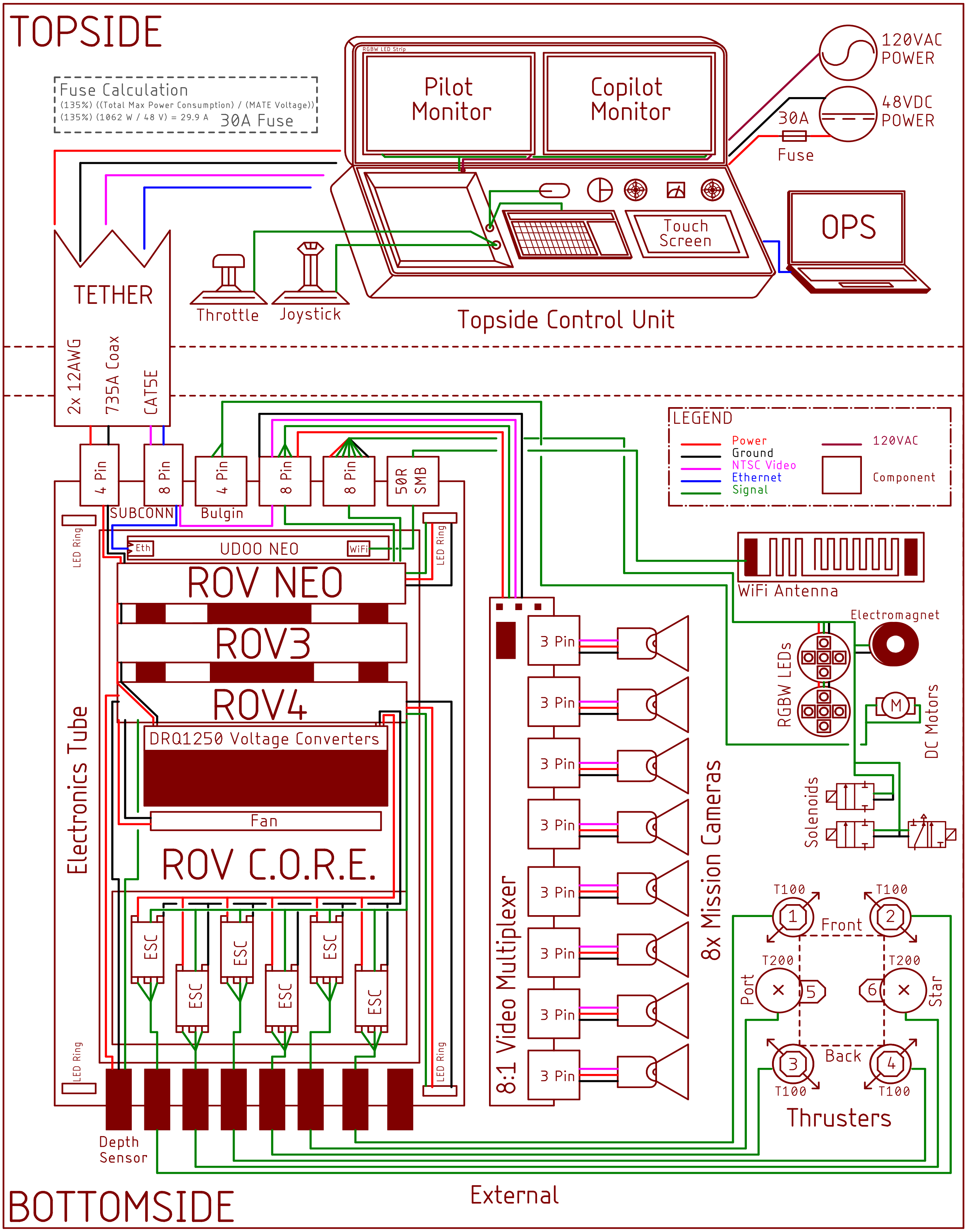


Figure 18. Electronics SID.

the use of waterproofed Bulgin connector. The video multiplexer PCBA is epoxy-potted in a custom tray housed under the wing of the ROV. The multiplexer was designed to provide compact form factor with eight individually removable cameras. The output of the multiplexer board is sent up the tether via the 735a coaxial cable and is encoded into a motion JPEG IP video feed by an Axis M7011 video encoder on topside. Digitally encoding the analog video signal allows for digital video processing, Heads Up Display (HUD) overlays, and more efficient video distribution between the pilot, co-pilot, and operations specialist.

Submersible Connectors

Mako uses a combination of Blue Robotics cable penetrators, SubConn wet-mateable electrical connectors, and Bulgin 400 series miniature power connectors. To reduce costs, devices that are permanently attached to the ROV, such as thrusters, use the permanent Blue Robotics cable penetrators. Other connections, such as those to accessories or the tether, utilize either the SubConns or the Bulgin connectors based on their usage. SubConns are used primarily for tether connections due to their insertion and desertion frequency compared to accessory connectors and the durability requirements that being on a tether imposes. Bulgin connectors are primarily used for connections to accessories because of their light weight, small size, and inexpensive cost relative to subconn connectors. Utilizing Bulgin connectors has helped expand *Mako's* peripheral capabilities while still keeping the ROV compact.

E. PNEUMATICS

Mako's gripper and lift bags are pneumatically powered using air that is regulated on-deck to 2.76 bar (40 psi) (Figure 20). The air is sent to the tools through a 6.35mm (0.25 inch) pneumatic line that was chosen over 3.18mm (0.125 inch) in order to increase the volume of air flowing to the ROV, providing quicker inflation of the lift bags. A solenoid that acts as a safety valve is housed in the TCU and can be controlled by the co-pilot via buttons on the TCU. Two additional solenoids are mounted on the ROV to control the flow of air to the lift bags. An additional solenoid mounted on the ROV controls the gripper. The pneumatics located on the ROV are controlled by the pilot by using buttons on the joystick. To simulate an operating depth of 5.5 m, we reduced the topside pressure to 2.22 bar (32 psi). At simulated 5.5 m, both the gripper worked and the lift bags inflated. This was also verified by operating at 2.22 bar while in the pool.

F. SOFTWARE

Overall

After reviewing the strengths and weaknesses of the company's previous software platform, Rovotics realized there was a lack of both processing power and a simple way to add, improve, and test features in bottomside programming. To remedy this problem, the company decided to use an UDOO NEO as the core of bottomside and an UDOO X86 as the topside controller. The UDOO NEO board has both native Linux and native Arduino capabilities[8] which allows for more processing power and a

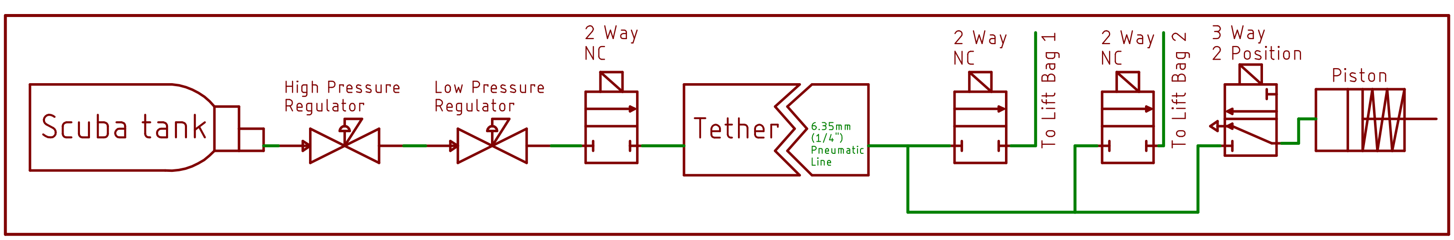


Figure 20. Pneumatics SID.

more straightforward approach to updating and testing the platform. The UDOO X86 was selected over the Raspberry Pi due to its increased performance and processing power. For software flowcharts, see Figure 21.

Topside

Rovotics' topside platform is written entirely in JavaScript server-side and HTML client-side on a Node.js web page platform that is executed using the UDOO X86 and operated with a joystick and throttle. The Node.js platform allows for asynchronous, event-driven execution, which prevents one process from blocking others and reduces latency for real-time processes. Both the client-side and server-side of topside start automatically on boot-up of the UDOO X86 in order to eliminate manual set-up time.

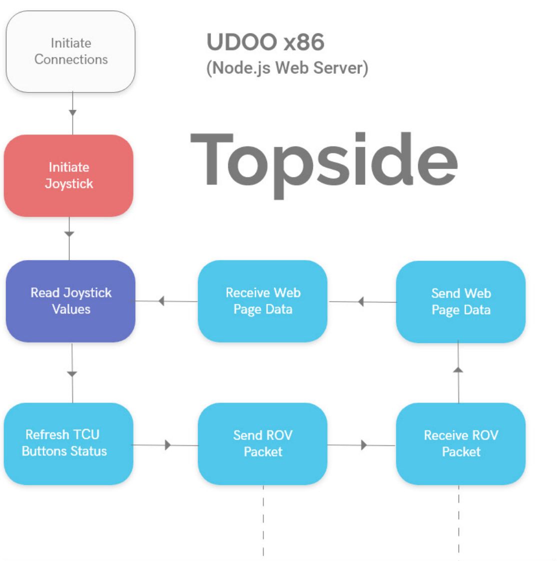
Topside features an intuitive Graphical User Interface (GUI) and a brand-new pilot HUD that displays telemetry data from the TCU and the ROV CORE. The GUI displays valuable data and pilot offloading functions. A GUI on the TCU touchscreen allows for intuitive controls of ROV functions such as ROV power and TCU based safety features. The platform also maintains several previously successful processes such as Rovotics' efficient vector drive algorithm, exponential proportional thruster control, and user-friendly hotkeys.

Bottomside

Mako's bottomside is centered around the UDOO NEO which uses two ARM cortex-A9 cores as its Linux computer and an ARM cortex-M4 core as an Arduino[8]. The A9 and M4 cores are both in constant communication with each other and topside. If communication is lost, the ROV enters into safe mode until communication is reestablished. In safe mode, thrusters, motors, and all other accessories are disabled.

The A9 cores use Python multithreading to run critical processes such as communication and vector-drive in a non-blocking mode. A PID controller in conjunction with an Inertial Measurement Unit (IMU) allow for smooth movement corrections with the adaptive depth hold function.

The M4 controls *Mako's* thrusters and PMC data which is relayed to topside by the A9. The M4 also reads data from *Mako's* power converters and humidity sensor.



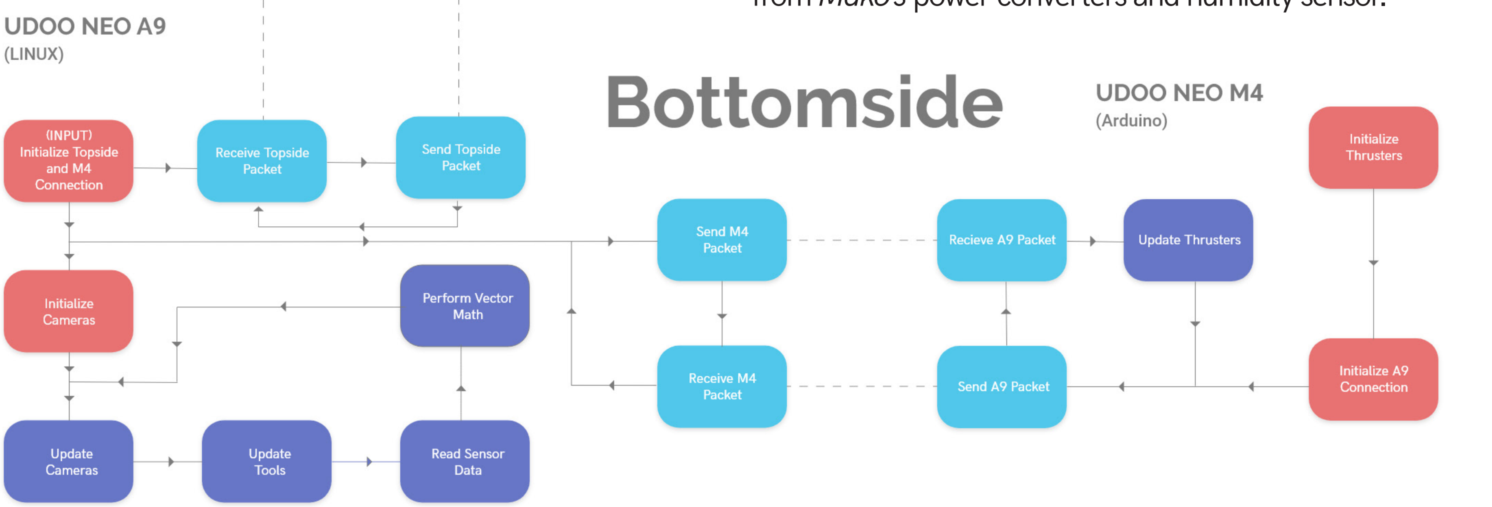


Figure 21. Software flowchart.

G. TOOLS

Handle Turn

The handle turn tool (Figure 22) is a 3D-printed, two-pronged insert mounted in a polycarbonate tube with a vacuum-formed polyethylene alignment cone on one end which levels the OBS. The cone assists the pilot in aligning with the OBS legs, and the insert grips and rotates the OBS legs to level it. The two-pronged design of the insert assists the pilot in maintaining contact with the handle even if the ROV shifts position while parked on top of the OBS. The handle turn is sealed by a double-shaft bayonet seal with a captive compartment for silicone gel between the double shaft seal.

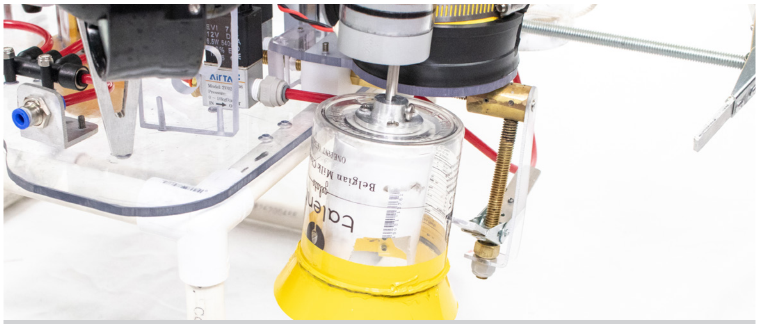


Figure 22. Handle turner.

Inductive Power Coupler (Power Puck)

The power puck's inductive coil (Figure 23) is powered by a 9 V battery and includes a 3 A fuse for circuit protection. The power puck incorporates a conic design for easier alignment and deployment into the OBS receiving port. It's held to the bottom of the ROV with an electromagnet.

Figure 23. Rovotic's power puck.

Acoustic Doppler Velocimeter (ADV)

The ADV (Figure 24) simulates the continuous measurement of water velocity at midwater depths and is

Figure 24. Rovotic's ADV.

contained in a delivery tube on the ROV. It attaches to a mooring line via a magnet.

Lift Bags

Mako is equipped with two different lift bags, the debris lift bag (Figure 25) and the engine lift bag, that are used to lift, transport, and release debris or engine blocks respectively from the wreckage area. Both lift bags use a toggle bolt with extended toggles to securely attach to the U-bolts mounted on the engine and debris. Once the lift bag is attached to the U-bolt, pneumatics inflate the bag.

The debris lift bag contains an acoustic release mechanism which is triggered by a microphone that listens for a preprogrammed acoustic pattern. Once the pattern is

Figure 25. Debris Lift Bag (right) and engine lift bag (left).

played, the lift bag motor rotates a jackscrew, releasing the debris. The debris lift bag then floats to the surface, to be retrieved by the deck crew.

Gripper

The pneumatic gripper (Figure 26) is used to install the base onto the bottom of the pool, place the turbine into the base, latch the turbine into place, and transport and lock the I-AMP into its stand. The gripper is comprised of two segments: a static side and a moving side. The gripper is made of three polycarbonate layers joined by screws and mounted on the bottom deck. The moving side is pushed by a pneumatic piston and is retracted by a return spring. The gripper is cut to provide pilot assistance by aligning with the objects held.

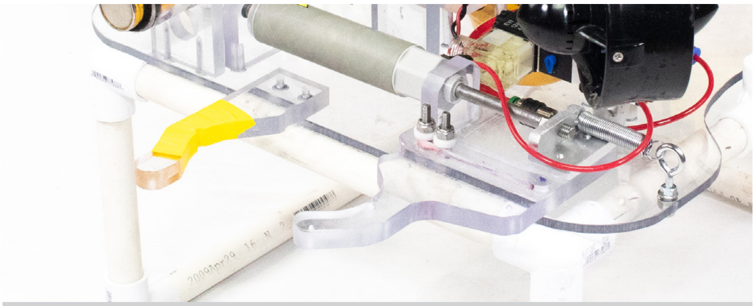


Figure 26. Gripper.

Software Tools

Rovotics' software tools include a uniquely trained Tesseract Optical Character Recognition (OCR) API for identification of the aircraft (Figure 27). Additionally, *Mako* has an integrated pixel ratio measurement feature that can find the appropriate distance from the tidal turbine base to the mooring base. In order to determine the height of

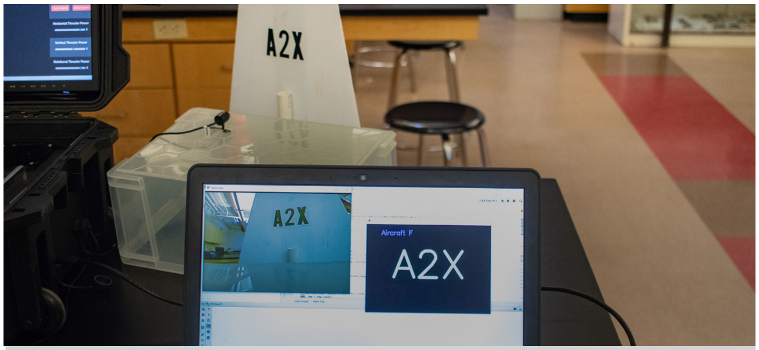


Figure 27. OCR identifying aircraft.

the ADV, *Mako* calculates the depth using its onboard depth sensor and displays it on the GUI. Finally, the inbuilt specialized calculator calculates the location of any plane, measures the tidal currents, and evaluates the power output of a turbine. The software tool results are displayed on the operation specialist's webpage.

H. PRODUCT DEMONSTRATION

Due to the variability in the tasks and the unforeseen factors that could occur during the product demonstration, Rovotics developed a Mission Strategy Board (Figure 28). The board contains relevant information about each of the mission tasks written onto sticky notes. Each sticky note includes risk values and a level of difficulty. This way, mission tasks can be efficiently and effectively judged to adapt the mission run to different conditions. The

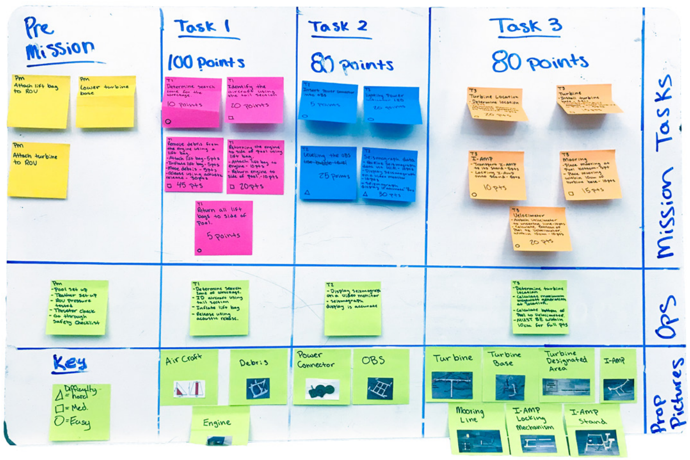


Figure 28. Mission Strategy Board.

Mission Strategy Board makes evaluating the mission tasks and designing tools to accompany them more streamlined, thus creating a more efficient mission runs.

III. TROUBLESHOOTING & TESTING TECHNIQUES

Rovotics began the troubleshooting process by identifying and isolating the problem through Root Cause Analysis (RCA)[6]. 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 size, weight, simplicity, cost, and time required.

The entire vehicle was tested in a full-scale "dry run" in which the vehicle was powered and bench tested in a controlled environment to ensure safety. The vehicle was then placed into a practice tank for several rounds of integration testing to determine its center of buoyancy, adjust camera positions, and find the vehicle's limits. To ensure customers receive a reliable, high quality product, Rovotics continued our practice of testing the complete ROV system for a minimum of 30 hours. Complete missions were run back to back by alternating crews for periods of three hours.

Individual tools and components were tested as a mock up prior to final design. Revisions were made during this time based on prototype performance and testing. For example, our original buoyancy tubes failed to provide the needed adjustability during testing in order to maintain a balanced ROV. This original design utilized larger length tubes to provide buoyancy, but this proved to be large and cumbersome. To remedy this, it was decided to use a mix of both the adjustable buoyancy tubes and foam buoyancy for a more efficient design. Once the design and manufacturing was completed, the components were tested individually to ensure proper function and water tightness if needed. When these steps are completed, the device is installed onto the ROV to evaluate operation and verify visibility with on-board cameras.

IV. SAFETY

A. 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 on the first evaluation. 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.

B. 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

Figure 29. Chemical vent hood

such as back safety, electrical safety, hazardous materials handling, housekeeping, and tool safety. Readily accessible Material Safety Data Sheet (MSDS)s 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 29). The work area maintains a negative pressure relative to the room, and fumes are carried up to a roof-mounted vent via ducting.

C. TRAINING

A peer-to-peer system is used for the safety training of new employees (Figure 30). Newly-hired

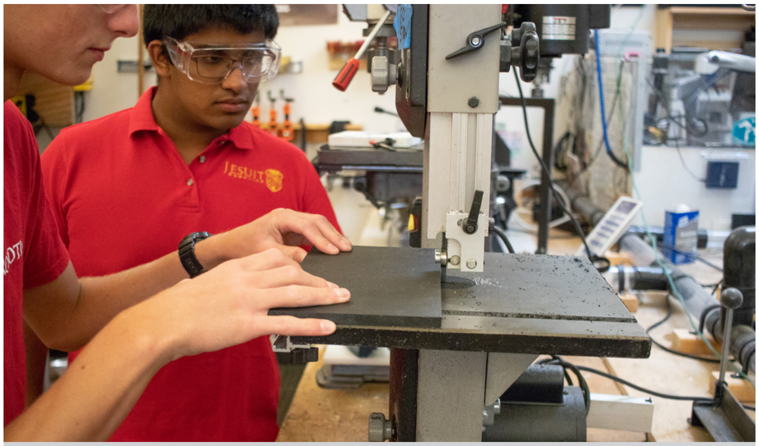


Figure 30. Rovotics' peer training system.

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. This season, Rovotics also developed 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.

D. 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 A) ensures that requirements mapped to multiple departments are addressed fully and independently. *Mako* has numerous safety features that keep the crew, work environment, and ROV safe during operation. A convenient handle on the ROV's top deck is clearly labeled for the deck crew to safely use during launch and retrieval, preventing injuries to personnel. Various waterproofing techniques ensure all electronics remain dry, protecting personnel and equipment from short circuits. A leak detector monitored by ROV CORE detects moisture and humidity in the electronics housing. If a leak occurs, the ROV status indicator notifies the pilot and shuts down *Mako*, which 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 acrylic housing allows for visual inspection of the electronics and a clear view of the RGB LEDs that indicate *Mako's* operating status. For example, green lights indicate that the ROV is safe to handle.

The newly-redesigned TCU incorporates digital displays for the crew to quickly determine if power delivery to the ROV is outside of safe operating values. A microcontroller monitors and displays current and voltage information to the pilot and co-pilot, allowing for quick shut-down in the event of any anomalies. If values outside of safe operating ranges are detected, a large power switch on the TCU can immediately cut power to the ROV (Figure 31).

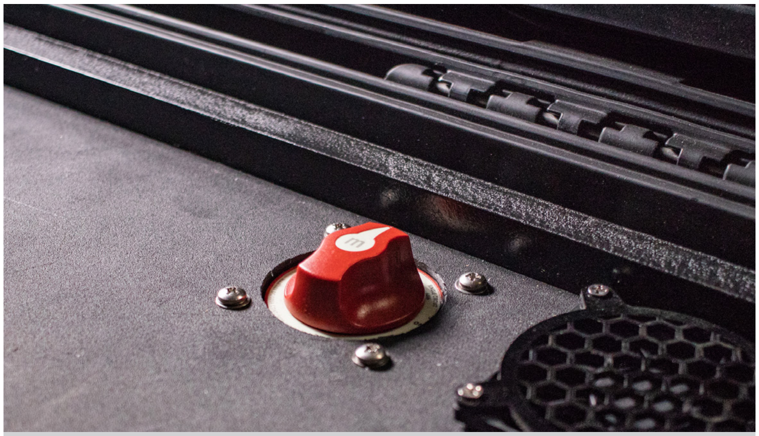


Figure 31. Large power switch on TCU.

E. OPERATIONAL AND SAFETY CHECKLISTS

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

V. LOGISTICS

A. SCHEDULED PROJECT MANAGEMENT

This year Rovotics continued to utilize the project management process to assist with managing department work assignments and overall project timelines. Rovotics uses a simple planning process involving sticky notes, task boards, and twice-daily standup meetings to optimize the product development Plan, Build, Test, & Release (PBTR) process. Implementing the PBTR system, each department used a task board that was populated with sticky notes for each task listing the employee responsible, a description of the task, and the due date. These notes were moved along a timeline by the department leads. Employees could refer to the board to track their progress and ensure they remained on schedule.

Tasks that applied to multiple departments had designated notes on a master schedule (Figure 32), which ensured that all employees were aware of upcoming deliverables required by MATE. This allowed the company to manage critical department assignments to ensure overall project expectations, while also providing additional exposure to project management for all employees. 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 task board, assign tasks to employees, and discuss individual progress. Between workdays, employees continued work on any daily production goals that were not met.

Figure 32. Rovotics' PBTR board.

B. 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, it's imperative that these 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 HUD display 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.

C. 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.

D. SOURCE CODE MANAGEMENT

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

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

E. BUDGET AND PROJECT 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 a CAM software update from Mach 3 to Mach 4, as well as ROVsim2, an ROV simulator software used at outreach events.

Income was estimated based on funding from Jesuit High School, donations, and employee dues. To ensure effective use of a limited budget, all purchases 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 2017-2018 Budget and Project Costing report is shown in Appendix C.

VI. CONCLUSION

A. CHALLENGES

Rovotics experienced interpersonal challenges in further refining the project management and organization process. Last year we introduced our new "PBTR" (plan, build, test, release) scheduling boards, which proved to be successful in defining specific tasks. However, it was difficult for employees to see and understand other department dependencies and the impact to the overall company timeline. For example, Software was challenged to meet their deliverables due to other department delays, causing tension between departments and employees. To address the issue, a few employees designed and created a distinct schedule board for each month so that employees could track their progress in terms of major deadlines. This way, employees could see how their deliverables corresponded with other departments in the final product. As a result, tasks were completed in a more timely manner as deadlines were more apparent.

The Electronics department endured significant technical challenges with the early assembly processes of the increasing complex ROV CORE series of printed circuit boards. Long build times limited board production to just a few per day and constrained the potential for an increased feature set due to physical limitation in the time allotted during board assembly. In order to decrease PCBA build times the Electronics department implemented a strict series of steps and build guide lines in order to properly organize parts during board assembly. This model focused on the increased efficiency of higher volume builds and the amount of time required to collect and organize all the required individual components. The result of the improved build techniques decreased overall build times by several hours and also contributed to an increased turnover of successful boards.

B. LESSONS LEARNED AND SKILLS GAINED

This year, Rovotics learned many key lessons throughout the development process. Early in the year, new employees joining the company were less familiar with existing processes and felt less included. To address this interpersonal challenge, departments partnered new students with older students for better integration into the company. The company also learned skills related to new machine tooling for the lab. Specifically, the company purchased a digital readout for the lathe and upgraded the CNC. With this upgraded equipment, students learned additional skills. Finally, during our electronics design process, our key technical lesson learned included the decision to buy off-the-shelf components instead of a customized PCB design. Originally, Rovotics went with the latter option, but the amount of work needed to complete the components proved to be inefficient, so it was decided to use a combination of pre-bought components and custom PCBs.

C. FUTURE IMPROVEMENTS

Along with improving stability and vertical maneuverability, Rovotics plans on upgrading the two current vertical acting T200 thrusters to four vertical thrusters. This year, Rovotics upgraded from two T100 thrusters to two T200 thrusters. While this configuration proved to have increased vertical mobility, it did not enable both pitch and tilt control simultaneously. While researching for this needed improvement, Rovotics observed several different thruster configurations, which should positively affect the vertical stability control.

Additionally, Rovotics would like to further expand a hybrid architecure combining potted electronics and tubular housed electronics. Using the potted video multiplexer design allowed for a significantly better form factor and an improved modular design of the camera platform. Building off this, Rovotics believes that further implementation of the potted board design in conjunction with an electronics tube can solve some of our remaining electronics problems, such as conector density on the faceplate and heat dissipation limitations in a highly compact electronics housing.

D. SENIOR REFLECTIONS

Sam Paragary

I would like to thank MATE for organizing the annual ROV competition, as well as the students and mentors of Jesuit Robotics for making such a valuable learning experience possible. The MATE competition and the four years I have spent with Jesuit Robotics team helped me develop technical and leadership skills far beyond what is taught in the classroom. I have gained skills and experience in project management, technical writing, mechanical engineering, as well as presentations to media, STEM-aspiring students, and the local community. There has been high points and low points, but they've all contributed to my growth as a student. I will be leaving Jesuit Robotics this year to study business administration and international relations at UC Berkeley. I'm confident that I will be able to apply the knowledge and skills I've gained from MATE and Jesuit Robotics for the rest of my career.

Noah Pettinato

I would like to thank all of the parents, students, coaches, Jesuit High School and MATE for putting in countless hours of work to create something as incredible as the underwater robotics competition. Without the collaboration of everyone, something as life-changing as this could not exist. The vast amounts of knowledge and lessons I have learned over these past couple years while being on the Jesuit Robotics team have been truly life-changing. Looking back on my high school experience, I am so grateful to be able to call this my second family. Hours upon hours of working, staying up late, and collaborating with like-minded individuals have made up the last three years of my life. I am sad to move on from this but extremely excited to see what the future has in store.

Risheek Pingili

First and foremost, I would like to thank all the students, parents, coaches, and especially MATE and Jesuit High School that make the robotics program a reality. As a fourth year member, I've had an amazing opportunity to further both my technical knowledge while increasing my ability and passion to solve software development problems. In my junior year, I was the Software Lead, where I spent a majority of my time teaching underclassmen the very same things I had learned in my early years on the team. There is nothing I love more than spending the whole day at the lab, building amazing friendships and gaining invaluable experience. None of this would have been possible without the environment provided by the Jesuit Robotics team and MATE.

Drake Charamuga

I'd like to thank MATE for hosting this fantastic competition and Jesuit High School for supporting our team. I appreciate my teammates and their parents, and I'd like to thank them for making this program into what it is today. I have learned so much about leadership, presenting, machining, CADD, electronics and programming through this competition. I was introduced to mechanical engineering through the MATE competition. It has not only become my favorite hobby, but I also plan to major in mechanical engineering at Long Beach State. I have had countless fond memories of testing our ROV in the pool during warm summer nights. My participation on the Jesuit Robotics team has defined my time in high school, and I know that my experiences will help me as I move on into the future.

E. ACKNOWLEDGEMENTS

- MATE Center and Marine Technology Society - Sponsoring this year's competition
- National Science Foundation - Their funding of the MATE competition
- Oceaneering International - Their support of the MATE competition
- Jesuit High School - Generous donation of funding and pool time
- Jay Isaacs, Head Coach - His time, creativity, knowledge, and guidance for the past thirteen years
- Steve Kiyama, Assistant Coach - His time, experience, and guidance for the team
- Cheryl Kiyama, Operations Manager - Her time, experience, and management of the team
- Jim Claybrook of Weldmasters - Welding services
- MacArtney Connectors - Providing connectors at a reduced rate
- GitHub - Providing complimentary private code repositories
- Travis CI - Providing continuous integration for private GitHub Repositories
- TAP Plastics - Donation of stock plastic
- SolidWorks - Donation of SolidWorks 3D Software
- Mentors - Heath Charamuga, Chris French, Craig Law, LisaMarie Isaacs, Jayanth Pingili
- Adobe Systems - Their generous donation to the team
- Our Families - Their continued support and encouragement

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VII. APPENDICES

A. OPERATION AND SAFETY CHECKLIST

Pre-Power

- Area clearsafe (no tripping hazards or items in the way)
- Verify power switches on TCU are off
- Tether flaked out on deck
- Tether connected to TCU and secured
- Tether connected and secured to ROV
- Tether strain relief connected to ROV
- Electronics housing sealed
- Perform Visual inspection of electronics for damaged wires, loose connections
- Nuts tight on 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 electronics housing
- 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

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
- ROV lights indicate “Safe Mode” (green)
- Test accessories

Launch

- Call out, “prepare to launch”
- Deck crew members handling ROV call out “hands on!”
- Launch ROV, maintain hand hold
- Wait for 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

- Pilot calls “ROV surfacing”
- Deck crew alls “ROV on surface”
- “Hands On”, thrusters disabled
- ROV lights indicate “Safe Mode” (green)
- 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
- Power down TCU
- 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

- Veriy thrusters are free of foreign objetcts and spin freely
- Visual inspection for any damage
- All cables are neatly secured
- Verify tether is free of kinks
- Verify 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 pneumatics system and open main valve

B. POWER BUDGET

Device	Quantity	Nominal Voltage (V)	Max power (W) per device	Total Power (W)
T100 Thruster	4	12	130	520
T200 Thruster	2	12	192	384
Blue Robotics ESC	6	12	6	36
ROV NEO CPU and MCUs	1	12	10	10
RGB LEDs	78	5	0.25	19.5
DRQ1250 Voltage Converter	2	48	19.2	38.4
Axis M7011 Video Encoder	1	48	15	15
Cameras	8	3.3	0.5	4
Solenoids	3	12	6.5	19.5
Video Multiplexer	1	12	0.1	0.1
Electromagnet	1	12	10	10
Brushed DC Motor	1	12	6	6
Total Power Consumption				1062.5
Total Avialable Power at ROV	Total Available Power at Input SubConn = (MATE Power) - (Tether Power Loss) = 1440 W - 270 W = 1170 W			
Fuse Calculations	(135%) ((Total Max Power Consumption) / (MATE Voltage)) = (135%) (1062 W / 48 V) = 29.9 A			
Fuse Value = 30 A				

C. BUDGET AND PROJECT COSTING

Production & Operations Budget	Project Cost	Difference
Available Income	$ -	
Total Budget		$ 21,189.00
Production ROV Costs	$ 9,372.83	$ 476.17
Research & Development Costs*	$ 1,132.83	$ (57.83)
Operations Costs* (includes travel)	$ 9,340.49	$ (575.49)
Capital Costs	$ 1,402.87	$ 97.13
* Budget overage due to Lodging & R&D Costs		$ (60.02)
Funds available for next season	$ (21,249.02)	

Project Costing Summary

Income	Budget	Type				
Jesuit School Funding	$ 14,450.00	Income				
Magazine Fund Raising	$ 2,500.00	Income				
Donations	$ 6,000.00	Income				
MATE Competition Awards	$ -	Income				
Employee Dues	$ 3,800.00	Income				
Total Income	**$ 26,750.00**					
Production Expenses	**Budget**	**Type**	**Expense**	**Description**	**Project Cost**	**Difference**
Frame & Housing	$ 1,100.00	Purchased	Production Materials	Acrylic tube, aluminum flanges, upper/lower deck	$ 1,015.55	$ 84.45
Thrusters	$ 1,300.00	Purchased	Production Materials	(4) T100 and (2) T200 Blue Robotics thrusters & ESCs	$ 1,250.03	$ 49.97
TCU	$ 600.00	Purchased	Production Materials	Case, Monitors, Electronics, Pneumatics	$ 542.41	$ 57.59
Tether & Connectors	$ 470.00	Re-used	Production Materials	Si wire, CAT5e, coax cable, sheathing, connectors	$ 416.00	$ 54.00
Electronics & Connectors	$ 1,100.00	Purchased	Production Materials	PCB Board Fab, components, connectors, cameras	$ 823.06	$ 276.94
Electronics Rework	$ 1,150.00	Purchased	Production Materials	PCB revisions and components	$ 1,244.45	$ (94.45)
Pneumatics	$ 100.00	Purchased	Production Materials	Valves, fittings, tubing	$ 80.45	$ 19.55
Mission Tools	$ 300.00	Purchased	Production Materials	Gripper, handle turner, lift bags	$ 409.36	$ (109.36)
Mission Control Center	$ 1,529.00	Re-used	Production Materials	Laptop, joystick; (re-used from 2017)	$ 1,529.00	$ -
Mission Control Center	$ 200.00	Purchased	Production Materials	UDOO X86	$ 188.75	$ 11.25
Raw materials	$ 2,000.00	Purchased	Production Materials	Plastics, metals, hardware, 3D filament, consumables	$ 1,873.77	$ 126.23
Production Budget	**$ 9,849.00**			**Total ROV Production Cost**	**$ 9,372.83**	**$ 476.17**
Research & DevelopmentExpe	**Budget**	**Type**	**Expense**	**Description**	**Project Cost**	**Difference**
ROV CORE Rev.0	$ 475.00	Purchased	SW Testing	PCB Fabrication, Development Boards	$ 503.27	$ (28.27)
Raspberry Pi Video Platform	$ 400.00	Purchased	SW Testing	Camera system interface video multiplexer, cameras	$ 433.56	$ (33.56)
UDOO Neo Kits	$ 200.00	Purchased	SW Development	SW kits for team members	$ 196.00	$ 4.00
R&D Budget	**$ 1,075.00**			**R&D Project Cost**	$ 1,132.83	**$ (57.83)**
Operations Expenses	**Budget**	**Type**	**Expense**	**Description**	**Project Cost**	**Difference**
Lodging	$ 7,600.00	Purchased	Travel Expense	11 hotel rooms for team/2 per room	$ 8,195.00	$ (595.00)
Mission Props	$ 300.00	Purchased	Production Materials	MATE mission props, blue tooth module	$ 297.00	$ 3.00
MATE Entry Fee	$ 300.00	Purchased	Competition fee	MATE entry fee	$ 300.00	$ -
Power Fluid Quiz Fee	$ 15.00	Purchased	Competition fee	MATE power fluid quiz	$ 15.00	$ -
Printing	$ 550.00	Purchased	Media Production	Report, display, brochure printing	$ 533.49	$ 16.51
Operations Budget	**$ 8,765.00**			**Operations Project Cost**	**$ 9,340.49**	**$ (575.49)**
Capital Expenses	**Budget**	**Type**	**Expense**	**Description**	**Project Cost**	**Difference**
Lathe Upgrade	$ 1,000.00	Purchased	Mechanical Developme	Lathe digital readout	$ 989.75	$ 10.25
Lathe Tooling	$ 500.00	Purchased	Media Publication	Quick-change tool post	$ 413.12	$ 86.88
Capital Budget	**$ 1,500.00**			**Capital Project Cost**	**$ 1,402.87**	**$ 97.13**
Employee Paid Expenses	**Budget**	**Type**	**Expense**	**Description**	**Project Cost**	**Difference**
Competition Meals	$ 2,625.00	Purchased	Employee Meals	Cash collected for competition meals; 21 people	$ 2,660.00	$ (35.00)
Transportation & hotel subsidy	$ 12,650.00	Purchased	Employee Travel	Cash contribution for car rental, gas, & hotel subsidy	$ 11,730.00	$ 920.00
Estimated Employee Fees	**$ 15,275.00**			**Actual Employee Fees**	**$ 14,390.00**	**$ 885.00**

Figure 33. Rovotics' Budget and Costing Sheet.