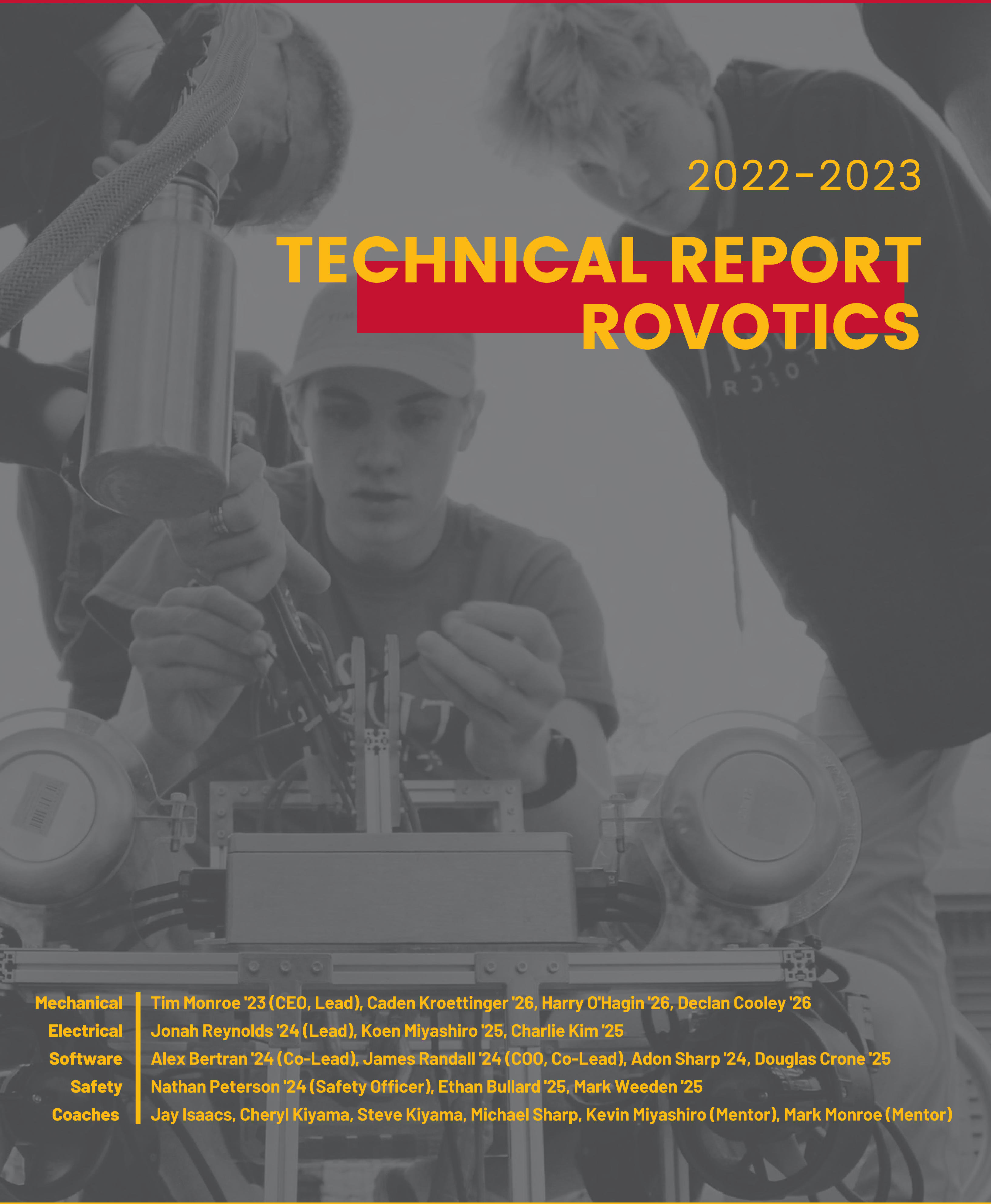

2022-2023

TECHNICAL REPORT ROVOTICS

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Jesuit High School | Carmichael, CA, USA

Introduction

ROVOTICS is a fourteen-person company (Figure 1) with years of collective experience in designing, manufacturing, and operating robotic solutions to ecological problems in aquatic settings. Tardigrade is ROVOTICS' newest and greatest Remotely Operated Vehicle (ROV) yet. It is equipped to install offshore solar parks, service ocean wind turbines, monitor and maintain coral health, and protect endangered aquatic species in a multitude of underwater environments.

Tardigrade is the culmination of years of ROVOTICS' design, development, and testing to meet quality and safety standards. The robust yet simple CORE-ROV system, composed of versatile hardware, expandible electronics, and an overhauled software platform, makes Tardigrade the most capable ROVOTICS product yet. This technical document outlines the planning and prototyping of Tardigrade that enable it to address the numerous challenges it will encounter.

Within this year's report, the ROVOTICS team is pleased to share our Engineering Design process that we use to consistently perform at a high level year after year. Numerous processes including our continuous learning model, lifecycle management, and safety first philosophy, all combine together to deliver a competition-ready ROV. By sharing this experience with the entire ROV community, we hope to raise the collective performance of all ROV teams in the future.

Figure 1. ROVOTICS Team Members

JESUIT ROBOTICS

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Acknowledgements

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Our Families - Their continued support and encouragement

MATE II

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JESUIT HIGH SCHOOL

Teamwork

Company Profile

ROVOTICS is a successful high school team dedicated to building ROVs aimed at sustaining Earth's resources and addressing environmental concerns, including climate change and humanity's impact on the environment. The team operates through three essential departments: Mechanical, Electrical, and Software, each led by a department lead responsible for managing assignments and priorities within their respective teams. The department leads play a vital role in determining department goals and assigning individual work tasks (see page 1 for specific member roles and responsibilities).

ROVOTICS places a strong emphasis on continuous learning and encourages cross-training among team members. Senior employees in each department take on the critical responsibility of mentoring and training junior team members throughout the entire development process. This approach establishes an effective succession planning model, ensuring the team maintains the necessary skill sets to create well-performing ROVs.

Resource, Procedure, & Protocol Management

ROVOTICS follows a multi-phase timeline (Figure 2) that frontloads the ROV development that is independent of the RFP / mission specifications. Phase I involves, creating an ROV that possesses "drive-and-see" capabilities. When the CORE-ROV is complete, ROVOTICS implements new improvements that do not relate to the mission spec, like this year's motion control software changes. This constitutes phase II. When the RFP is released, the final phase sees ROVOTICS design mission-specialized tools and functionality, as well as perform rigorous testing. The final integration between the CORE-ROV and tools is validated in conjunction with Deck Crew mission practice in a mission-like aquatic environment. Throughout each of the development phases, ROVOTICS followed an Engineering Design process which included planning, prototyping, testing, integrating, and documenting, to ensure repeatability and reliability across all systems.

The following sections will provide detailed information about the ROV's development, and share examples of how the Engineering Design process played an important role in building an on-time, reliable ROV ready to tackle the mission challenges.

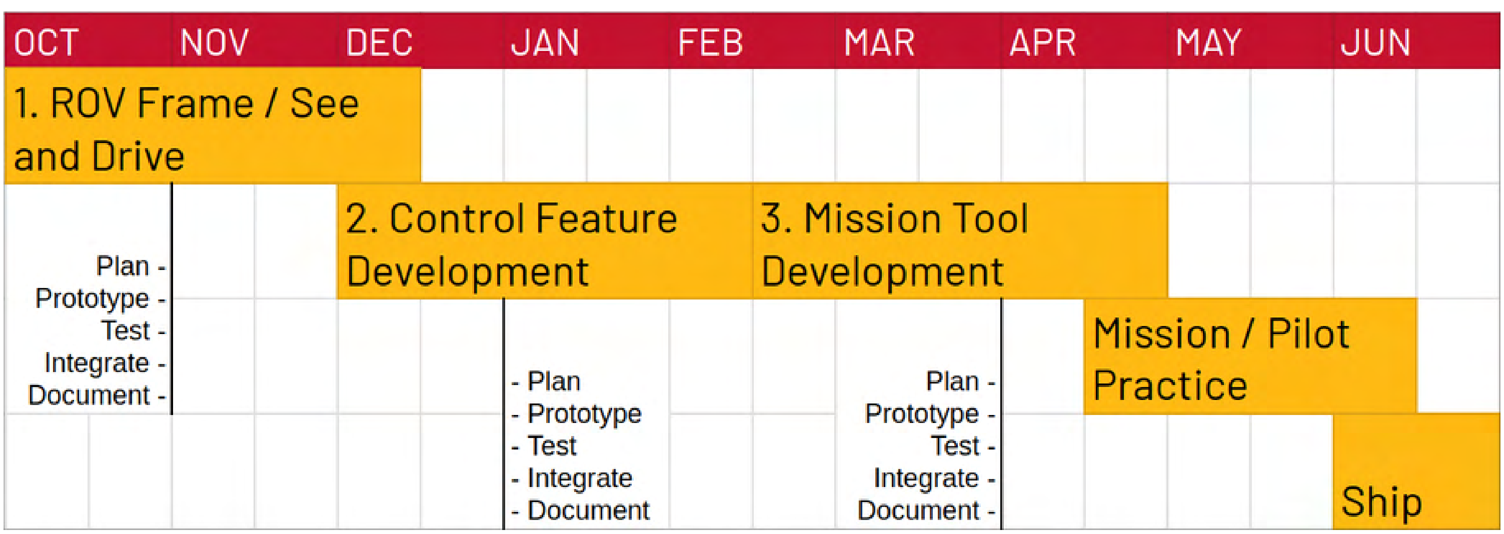


Figure 2. Project Schedule

The phases in Figure 2 are broken down as follows:

Phase I: CORE-ROV drive-and-see Capability

- Design and implement the fundamental ROV propulsion and vision systems

Phase II: Control feature Design and Development

- Create and refine control features for enhanced functionality using lessons learned from previous years' ROVs.

Phase III: Mission Tool Design & Dev and Product Demonstration

- Design and develop specialized tools for accomplishing mission-specific tasks and integrating once verification testing is passed.
- Conduct simulated mission runs to train the deck crew in handling the ROV. This phase also tests the ROV's operational capabilities in addressing the specific demands of the mission tasks through 40+ hours of pilot practice
- Prepare the ROV for its ultimate deployment by packaging and shipping it.

Project Schedule

ROVOTICS department leads conduct weekly virtual meetings to discuss the progress of company-wide projects and provide updates on the status of each department. These meetings allow team members to share their achievements over the past week with the entire team and discuss plans for the upcoming week to ensure that the projects remain on schedule.

To create a clear and easily accessible schedule, ROVOTICS uses a Kanban board (Figure 3) where mission tools and ROV build tasks are tracked. The board utilizes a sticky note and colored dot system, making it easy to modify the schedule and identify items that require additional attention. This system ensures that the team remains efficient by quickly reallocating resources where necessary. At the beginning and end of each workday, the team holds a standup meeting (Figure 3) to review and update the board. By using an interactive scheduling system that is easily updated, the team is able to stay on track and meet project deadlines.

Figure 3. Standup Meeting

Design Rationale

CORE-ROV Overview

ROVOTICS capitalizes on the successes of our previous ROVs to produce our current, fourth-generation ROV. Reusing core systems allows the team to rapidly produce a new ROV mechanical frame with electronics and control software. This requires a minimal redesign, which manages risk, resulting in a more predictable schedule with a validated ROV early in the season.

ROVOTICS' ***engineering design rationale*** focuses on a modular frame system similar to the previous year's proven design which has gradually evolved. It is composed of beams of 15 x 15 mm extruded aluminum with T-slots. Aluminum extrusion and a wide assortment of fastening solutions are readily available from many online suppliers, supporting a reliable standardized manufacturing process. The mechanical design is that ROV tools can be mounted to any point on the frame thanks to the use of quick-release pins and aluminum mounting rails on each tool, contributing to a modular configuration that is quickly adaptable to changing conditions during missions.

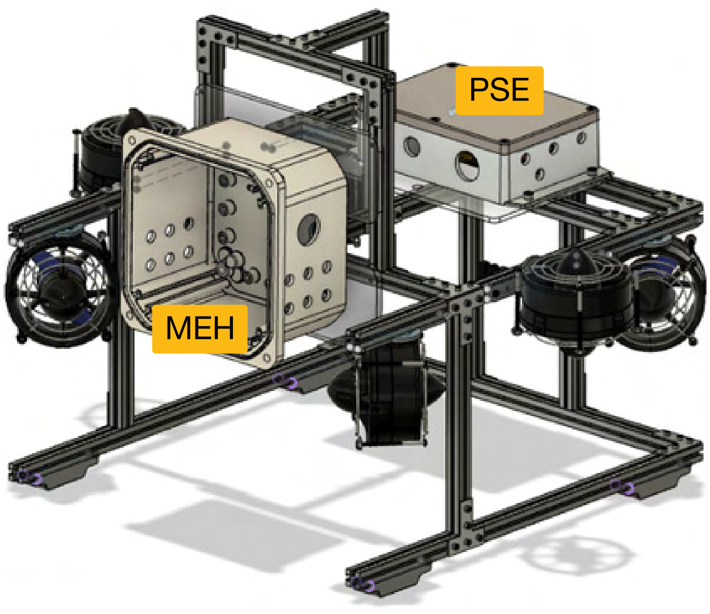


Figure 4. *Tardigrade's* CORE-ROV Frame

Tardigrade's electrical system consists of two main parts: control electronics housed in the MEH (Main Electronics Housing) and ROV power electronics housed in the PSE (Power Supply Enclosure). The Main Electronics Housings and Power Systems Enclosure are mounted to the top frame (Figure 4). The clear and flexible Electrical Tube connects the housings together to provide power to the MEH and data to the PSE. This year ROVOTICS modified the previous design by adding more penetrators, allowing more connections from the electronics in the MEH. These connections can be used for any electronic needs outside the MEH and PSE, such as cameras, peristaltic pumps, solenoid valves, and lights. To ensure serviceability, a new PSE circuit board was designed to standardize connectors and reduce wiring, making installing ESCs into the housing easy.

Design Process

ROVOTICS follows a systematic design process for every ROV manufactured. We utilize a thorough brainstorming process that enables engineers to approach problem-solving in an organized manner, fostering the improvement of existing designs and the creation of new ones. Each year, ROVOTICS revisits their original ROV concepts from previous years, with the goal of improving upon previous CORE-ROV system functionality. This re-evaluation process enables ROVOTICS to reuse reliable systems, effectively reducing development time.

Design decision matrices are used to guide the design process (Figure 5), allowing ROVOTICS engineers to assess the effectiveness of a product in terms of its price, manufacturability, and capability. Quality designs are then evaluated with each other to analyze trade-offs, further narrowing down designs. Once a decision is made, ROVOTICS assigns projects for design to its various department members.

Criteria	Weight (1-5)	Windows, ROS Native	Score	Windows, ROS with WSL	Score	Windows No ROS	Score	Ubuntu, RC with Wine	Score
Stability	5	2	10	4	20	4	20	1	5
Ease of Setup	2	1	2	3	6	3	6	0	0
Ease of Use	3	3	9	3	9	3	9	2	6
Ease of Development	3	1	3	2	6	3	9	1	3
Integration	2	2	4	4	8	0	0	4	8
Totals:			28		49		44		22

Figure 5. Sample Decision Matrix for Selecting Photogrammetry Operating System

ROVOTICS' successful ROV designs, seamless integration, and punctual ROV delivery can be attributed to the ***innovative*** test benches (Figure 6) that simulate the ROV functionality. This year, the software department implemented new virtualized environments that allowed code to be tested without access to ROV hardware. Following our verification and validation approach, these modern tools allow us to innovate and iterate without destabilizing the ROV's existing software. For example, when the initial ROV was still under construction, the software department was able to refactor the vector drive code and fully test it in a simulated software environment beforehand. Once the ROV structure and control systems were ready for software integration, the ROV bring up progressed much more quickly because all the software had already undergone thorough verification testing.

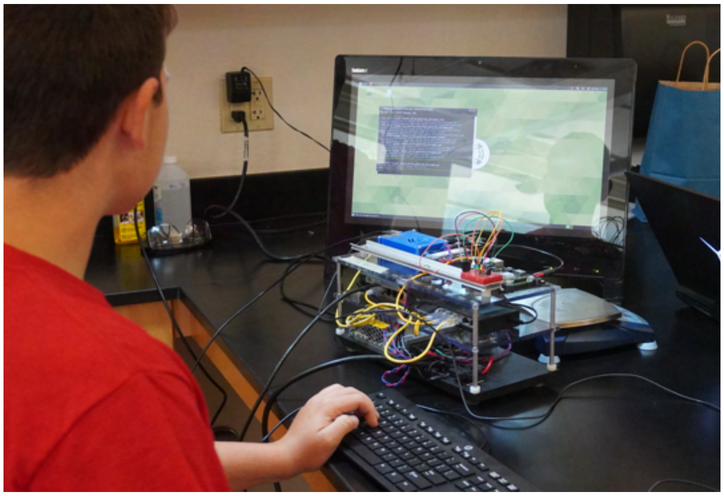


Figure 6. Software Engineer at Testbench

During tool production, the mechanical team realized that the existing gripper design required extensive CNC machine time. As the existing gripper design was reviewed. The team took advantage of a commercial water jet cutting service to "blank out" the main aluminum member of the gripper. This small design change resulted in a simpler, more efficient machining process by reducing cost and machining time by two-thirds. As the team already had extra parts on hand from the previous production run, this improvement will be forthcoming on the next iteration of our ROV.

Problem Solving

Toward the end of the 2022 season, a significant reliability issue with the motor control of the thrusters was identified. ROV changes were postponed, and ROVOTICS placed a priority on reworking the speed controllers for the new year. This particular problem required input from all three departments. The mechanical department was concerned with adding more hardware into an already compacted PSE. The software department objected to the current solution's use of C++ because the language introduced complexity that made the process of onboarding new members more difficult when compared to a language like Python. The electrical department was concerned with the current solution utilizing USB as the communication protocol. During the problem-solving session, the team researched industry-standard solutions to motor control and commonly used communication protocols. In the research phase, all options were assessed via a decision matrix, and a dedicated PWM controller chip using I2C as the communication protocol (Figure 7) was selected as the clear winner. It was chosen for three main reasons:

- Familiarity with the I2C communication protocol because it was used in reading pressure sensor data.
- I2C uses only 3 cable leads with standardized connectors.
- The PCA9685 PWM controller has a small form factor that easily fits within the constraints of the PSE.

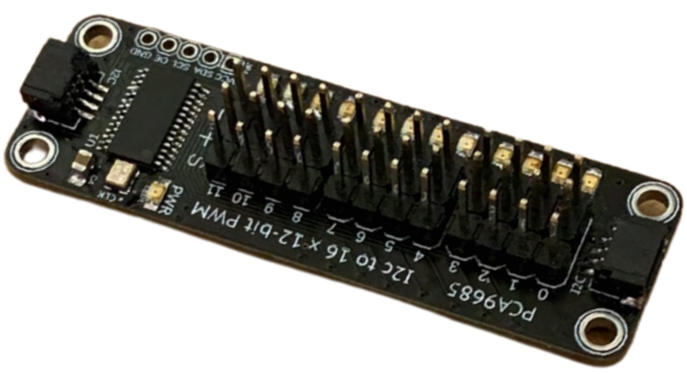


Figure 7. ROVOTICS Custom PWM Controller

Systems Approach

As shown in Figure 5 and previously mentioned, ROVOTICS has a multi-phase ***system design approach*** to mitigate risk to the final system integration by building most of the mission-independent modules early. In Phase I, the focus is on building the CORE-ROV and implementing basic Drive-and-See functionality. Next, Phase II includes the development of enhanced control features, while Phase III adds mission-specific tools.

To minimize the risk of a last-minute schedule crunch, a proven, stable, CORE-ROV design was used for the fourth year running. This CORE-ROV, with the basic capabilities of Drive-and-See, contains a mechanical frame, an electronics system, and a standardized software control system that have all been incrementally improved with time. By producing the initial ROV before the installation of all mission tools, we establish a stable foundation that undergoes thorough testing and validation well before the mission specifications are released. This approach provides a reliable starting point for subsequent mission-specific modifications and enhancements. Through evolution and reuse, successful designs of core functionality can be relied upon, allowing team members to dedicate more time to the production of new innovative mission tools. ROVOTICS teaches new employees critical skills by involving them in the frame production process each year. This allows new members to learn how Tardigrade works without being forced to design new components with minimal knowledge of the ROV.

When the CORE-ROV is completed and the mission specifications are released, the next design phase of implementing new tools is started to develop a fully functioning robot. When assessing the ***"New versus Used"*** dilemma, ROVOTICS makes decisions by reviewing tools from prior years. Wherever possible, existing tools are repurposed, which is a powerful example of our prioritization of evolutionary over revolutionary practices in our design philosophy.

One example of this is the Lift Bag Tool (Figure 8) introduced this year. It is a combination of a lift bag and two scissor clamps, and it was developed based on a design that has already been proven successful in the past. Other tools, which must be designed from scratch, are the reason for the heavy focus on evolution. By spending less time, money, and effort on redesigning parts and tools that have already been proven, more resources can be focused on the design of brand-new tools to be used in competition and stored in the repertoire to continue building upon this strong method.

Figure 8. Pipe Gripper Tools

As an example of ROVOTICS' commitment to modularity, we standardized the tool power bus to provide 12 volts to all tools. We switched to the use of I2C for all command, control, and communication. Keeping every tool and sensor on the same standards means every power wire, communication wire, and port can be shared, moved around, and easily replaced. This modular design change helps cut costs and simplifies the overall design of the tool and electronics systems, which allows ease of continuation in the future.

Mission-specific tool development begins the moment MATE releases the RFP. Design priority is given to multi-purpose tools such as the gripper, which can perform a variety of tasks and can be augmented with custom-made attachments to meet specific needs.

Vehicle Design

Vehicle Structure

Tardigrade's Vehicle Structure (Figures 9-12) consists of a lightweight exoskeleton comprised of aluminum extrusions. Previously, 20mm x 20mm aluminum extrusions were used. However, the tradeoff to 15mm x 15mm was made to take advantage of the improved weight-to-size ratio with minor sacrifices to strength and rigidity. This frame material can be reconfigured quickly through the use of brackets and screws, which speeds up the development process. The flexibility and modularity of the frame material allowed us to adapt it to this year's missions. ROVOTICS efficiently cuts the extrusions to the proper lengths in a way that produces the least possible amount of waste, which reduces costs because the remaining material can be reused in future frames. The vehicle structure also includes the electronic housings chosen from off-the-shelf retailers for their all-weather durability, then customized for our mission-specific ROV design requirements. The MEH (Main Electronics Housing) was chosen for its clear front panel and polycarbonate design. The PSE (Power Systems Enclosure) was chosen for its aluminum design, allowing efficient heat dissipation. Because of the customized variants we fabricate, ROVOTICS saves time and money in building our vehicle structure instead of building components from scratch.

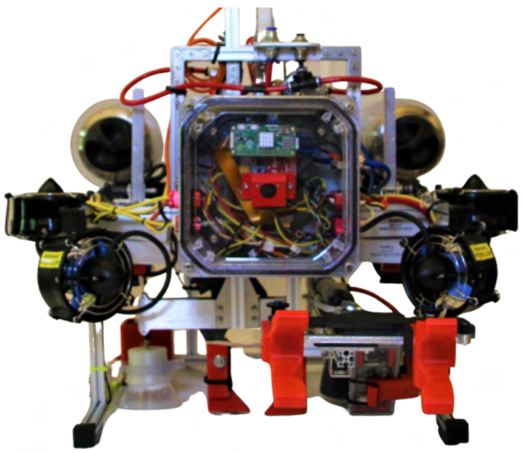
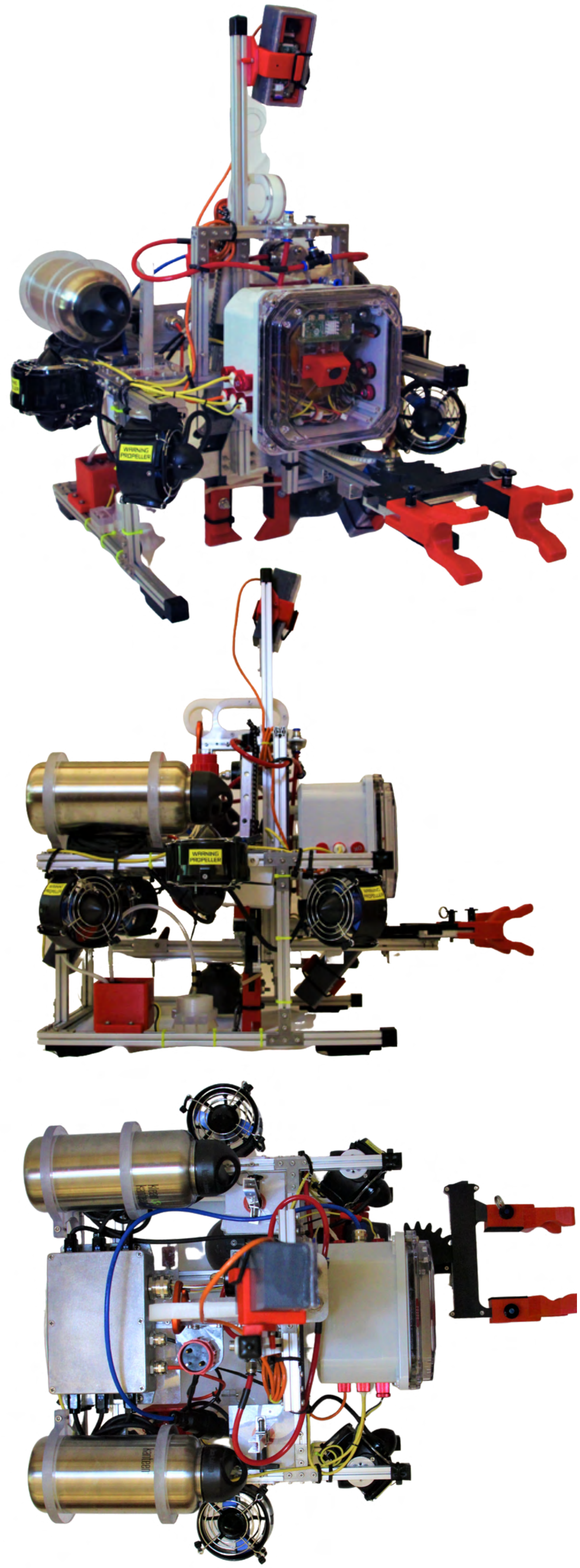


Figure 9. ***Tardigrade*** **ROV (Front)**



Figures 10-12. ***Tardigrade*** **ROV (Perspective, Side, Top)**

Electrical & Control Systems

There are two major electronic systems. For simplicity, they are Bottomside (Below water surface) and Topside (above water surface). They are described below and also detailed in Figure 16 and the SID (Appendix A1).

Bottomside

Within the ROVs Main Electronic Housing (Figure 13), a Raspberry Pi 4 runs all ROV control processes. A custom Dev/Relay HAT (hardware attached on top), seen in Figure 14, extends the General Purpose Input/Output (GPIO) native on the Pi. It is designed to accept a plethora of Commercial Off The Shelf (COTS) sensors due to the two peripheral bays that allow easy mounting and standardized connectors. *Tardigrade* uses a depth/pressure sensor, a 9-axis IMU (Inertial Measurement Unit), and sensors for leak detection.

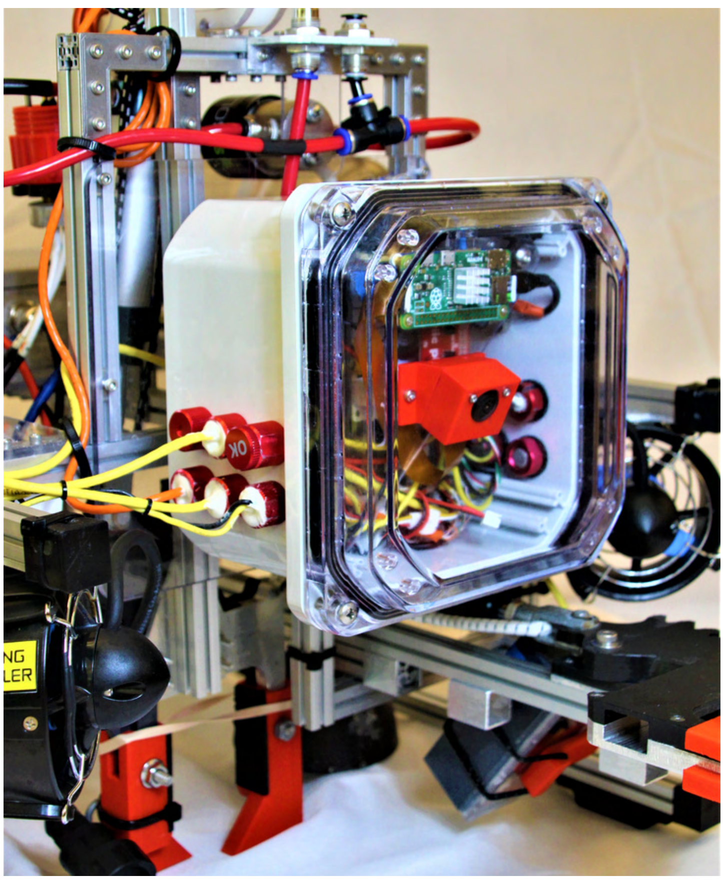


Figure 13. Main Electronics Housing

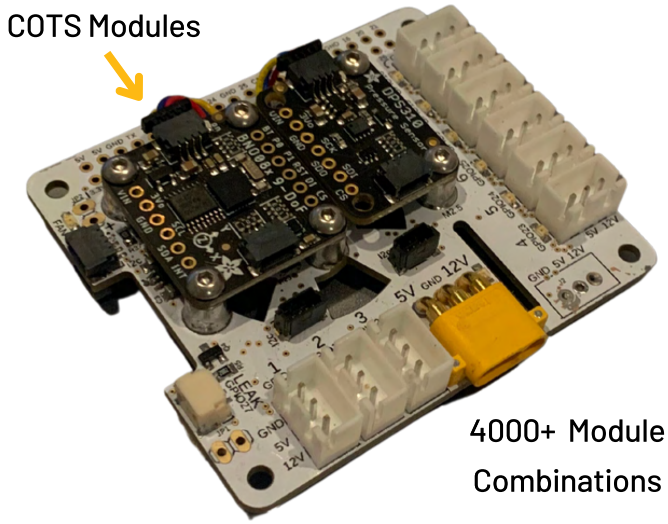


Figure 14. ROVOTICS Custom Dev/Relay HAT

Power Conversion and Thruster Control

ROVOTICS designed a custom power board to convert the 48V supply with two larger converters providing 12V and up to 1200W of power for thrusters and power-hungry tools, while a smaller converter provides 5V for control electronics such as the Raspberry Pi 4 and Ethernet switch. For safety, all have overvoltage, ubndervoltage, overtemperature, and overcurrent (short-circuit) protection. The board was designed with a modular open architecture in mind to allow industry-standard components to be easily mounted, connected to the board, and maintained without needing to resolder components. Blue Robotics ESCs are mounted to custom adaptor plates that allow for plug-and-play mounting, with low profile clearances to fit within the enclosure (Figure 15).

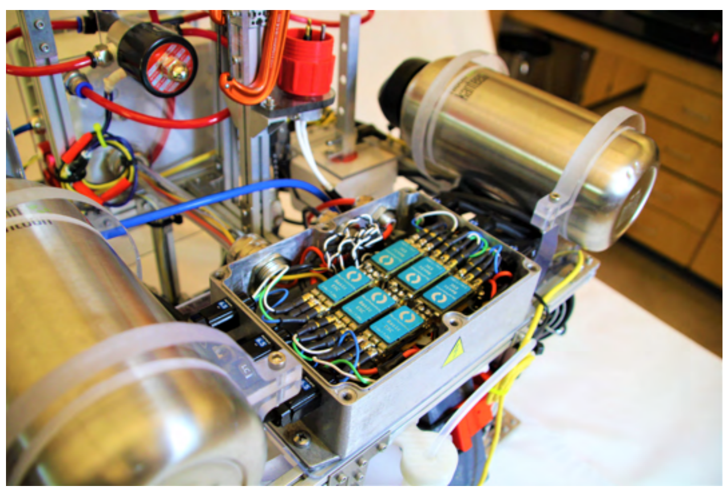


Figure 15. Power Supply Enclosure

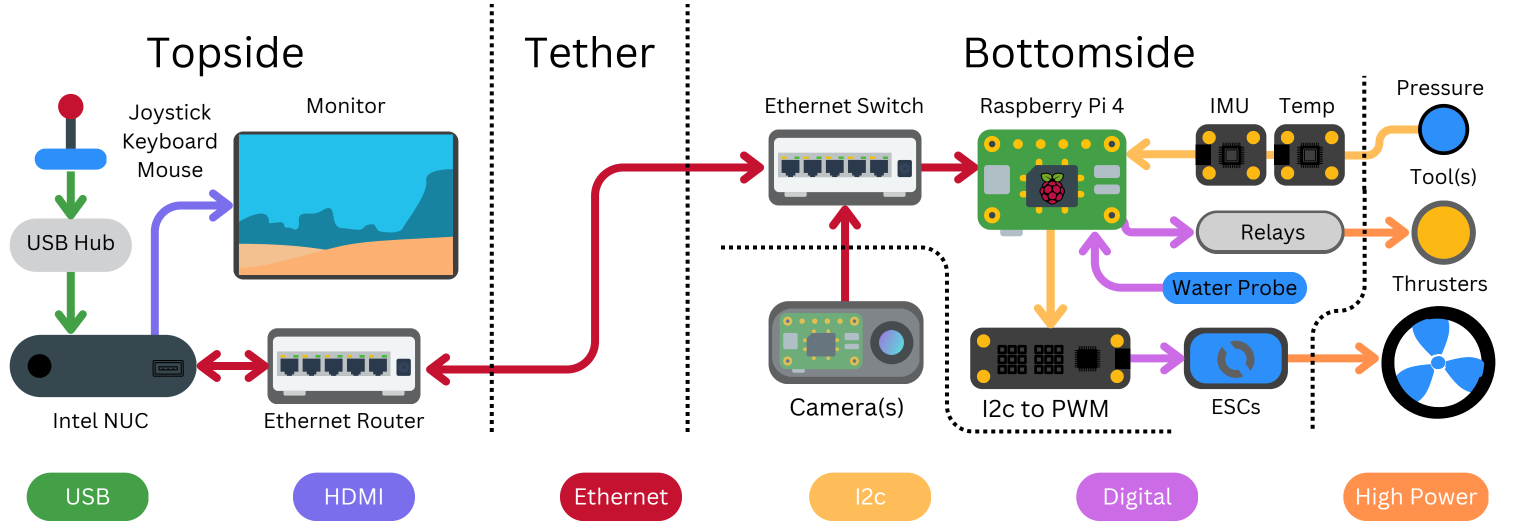


Figure 16. Control System Flow Diagram (For more detailed SID see Appendix A1)

Vision and Networking

Navigation of the ROV and operation of mission tools require high-quality images delivered with low latency to give the pilot and copilot the best chances of success. *Tardigrade* is fitted with five cameras (Figures 17 & 18), one dedicated to navigation and four for mission-specific tools. Mission-specific tool cameras require a single penetration as data and power each uses two pairs of a standard Cat 6a ethernet cable. Within the water-tight enclosure, each camera consists of a pogo style ethernet board, a Raspberry Pi Zero, and a Raspberry Pi camera sensor. The camera uses open-source Linux shell tools to stream video at 30 frames per second at 720p resolution.

Another way that ROVOTICS handles the ***build vs buy*** dilemma is by purchasing items that meet our requirements if the choice is reasonable in terms of performance and cost. The electronic components for the cameras were beyond ROVOTICS' manufacturing capabilities, so they were purchased, and commercial options performed suitably at reasonable prices. However, similar camera housings are not available commercially, so ROVOTICS manufactures those components in-

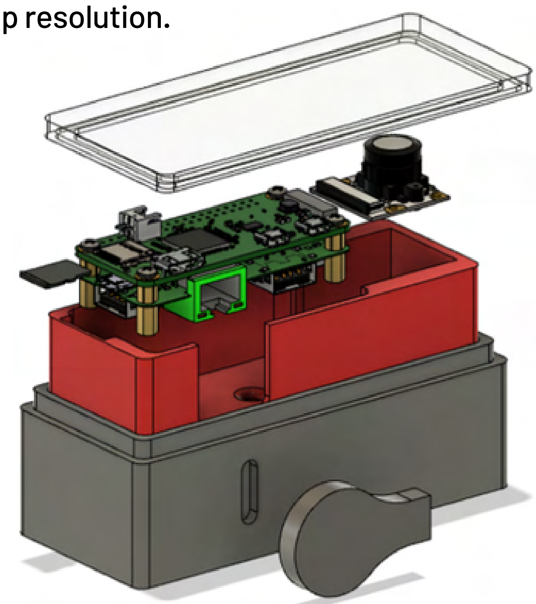


Figure 17. Digital Camera CAD

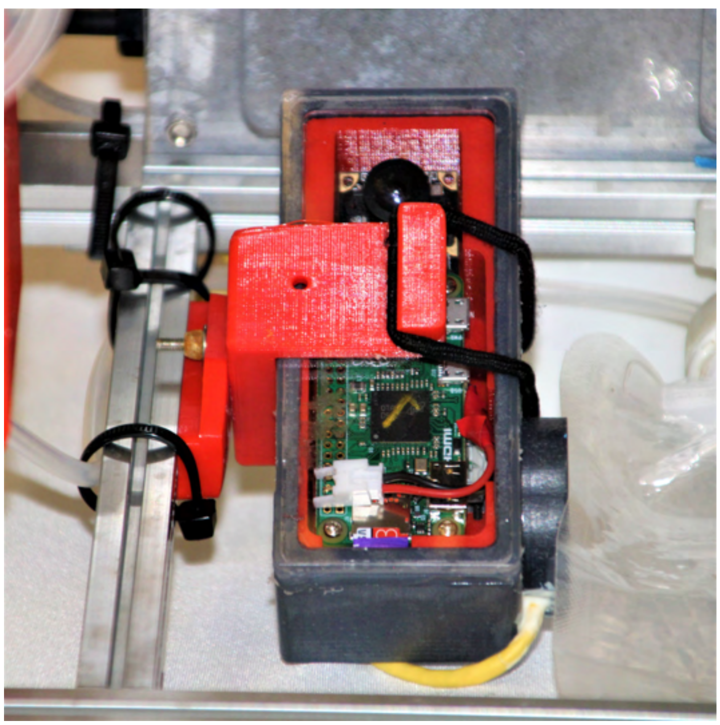


Figure 18. Digital Camera

house. This meant that critical components in the ROV, like the aluminum frame were custom designed by ROVOTICS in order to meet all mission specifications.

Tether

The tether is designed to offer reliable electrical power, compressed air, data transmission, and a physical connection to the ROV, all while allowing unrestricted movement. To increase safety during operation, all lines are protected within a flexible and brightly-colored sheathing that enhances visibility. Power is transmitted to the ROV through a pair of low-resistance 10 AWG wires that were selected after a thorough analysis of flexibility and power stability under heavy current loads. Pneumatic lines were chosen to maximize airflow and flexibility while adhering to the safety specifications provided by MATE. Each gripper is served by an individual pneumatic line, and one line is shared with the lift bag. Data is transmitted at gigabit speeds between surface control and the ROV via a Cat 6A Ethernet cable. Buoyancy nacelles enable the tether's profile to be dynamically adjusted to best meet mission requirements and differing environments.

ROVOTICS' Tether Management Protocol is a culmination of over a decade of experience, prioritizing crew safety, mission effectiveness, and practical implementation. During operation, the tether constantly remains in human control with ROV supervision (Figure 19). A post-mission maintenance protocol ensures the tether is properly rolled and stored to prevent twists and connector damage. An operational protocol is handled by two on-deck personnel ensuring safe mission usage.

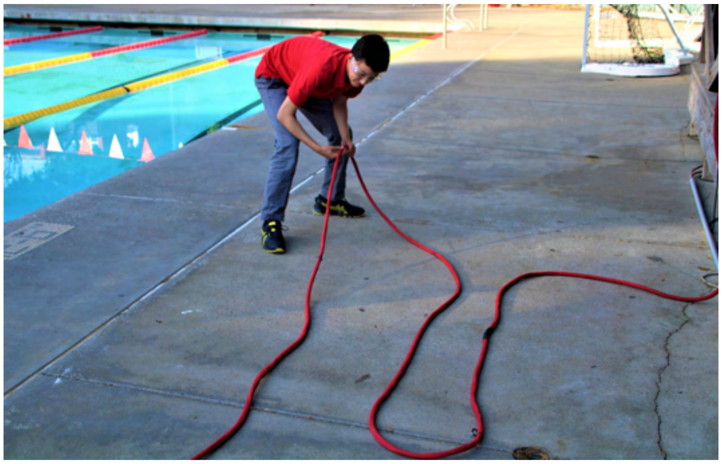


Figure 19. Employee Demonstrating Tether Handling Protocol

Topside

All primary surface control systems are housed in the compact Topside Control Unit (TCU) (Figure 20), which has been reused from last year as part of a multi-year control model. The TCU contains a powerful desktop computer (Figure 21) and a monitor set into the lid, enabling operators to view the ROV's camera and control it using the Graphical User Interface (GUI). The TCU also features bulkhead connectors for USB, ethernet, power, and pneumatics. Strain relief attachment points secure a strong connection to the TCU.

Figure 20. Topside Control Unit (TCU)

Figure 21. TCU Interior

Safety features include both a current and voltage meter, which monitor ROV and TCU power supply conditions, and a highly visible main shut-off power switch.

Propulsion

Tardigrade's propulsion is managed by six Blue Robotics T100 thrusters. These were chosen because they are lightweight, reliable, and safe. We also wanted to support Blue Robotics because they have a robust community and support forum in addition to being a MATE sponsor. To ensure safety to operators, each T100 has thruster guards (Figure 22) and operates at a maximum power consumption of 130 watts, which is within Tardigrade's power budget. Four of these T100 thrusters are mounted at 45° angles on the corners of the ROV frame. This allows the ROV full lateral motion. The remaining two thrusters are mounted vertically either side of the ROV's frame allowing vertical propulsion.

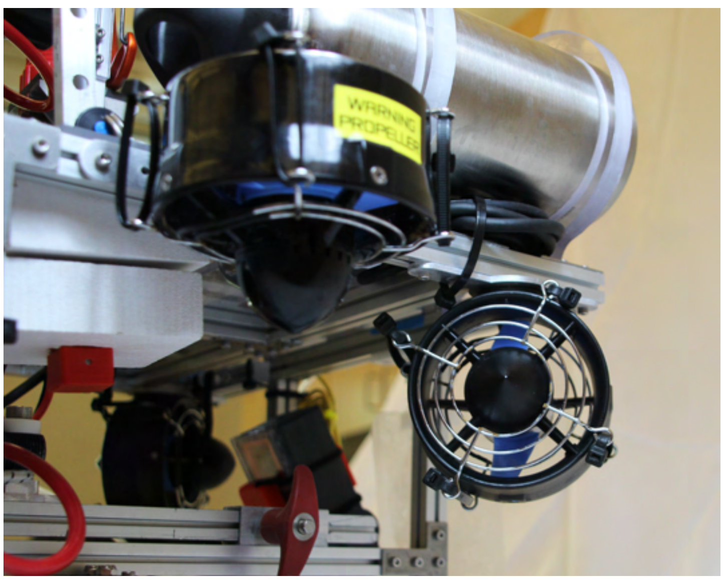


Figure 22. ROV Thruster

Buoyancy & Ballast

Using Archimedes' Principle, ROVOTICS determined that Taridgrade's buoyancy and ballast needed to support 12-13,000 cc (12-13 kg) of displacement (See Appendix B1 for calculations) To tackle this, ROVOTICS divides the buoyancy system into two distinct components: static and dynamic. The static component (Figure 23) is comprised of two incompressible stainlesssteel nacelles and the volume within the MEH and PSE that address a significant portion of the buoyancy. The dynamic component (Figure 23) utilizes 137 cc foam float cubes as a standardized volume, optimal for balancing the ROV's pitch and yaw while providing slight buoyancy to support the remaining mass. By dividing the system this way, ROVOTICS has manufactured an efficient and modular buoyancy system.

Figure 23. Dynamic (Left) and Static (Right) Buoyancy Systems

Payload & Tools

Tardigrade has four ultra-wide angle real-time streaming cameras to give the pilot ideal vision while navigating the ROV or performing mission tasks. These cameras are strategically placed throughout the ROV to enhance the pilot's situational awareness. They are carefully positioned to deliver consistent camera views aligned with the ROV's motion.

The ***camera placement*** is designed so the pilot has visual data that gives feedback to the center line of the ROV. The top view helps to see where the entire ROV is relative to the surroundings. The navigation view allows the pilot to see the front gripper and it is also in the optimal position for controlling the ROV due to its fixed position. The under-view allows for viewing of the lower gripper and various other tools mounted to the bottom of the ROV. The lower front view is for coral modeling and viewing the mooring hooks while being held by the gripper.

These camera placements ensure that the pilot has an enhanced visual understanding of the ROV's surroundings and crucial components, optimizing their ability to navigate and perform tasks effectively.

Payload & Tools

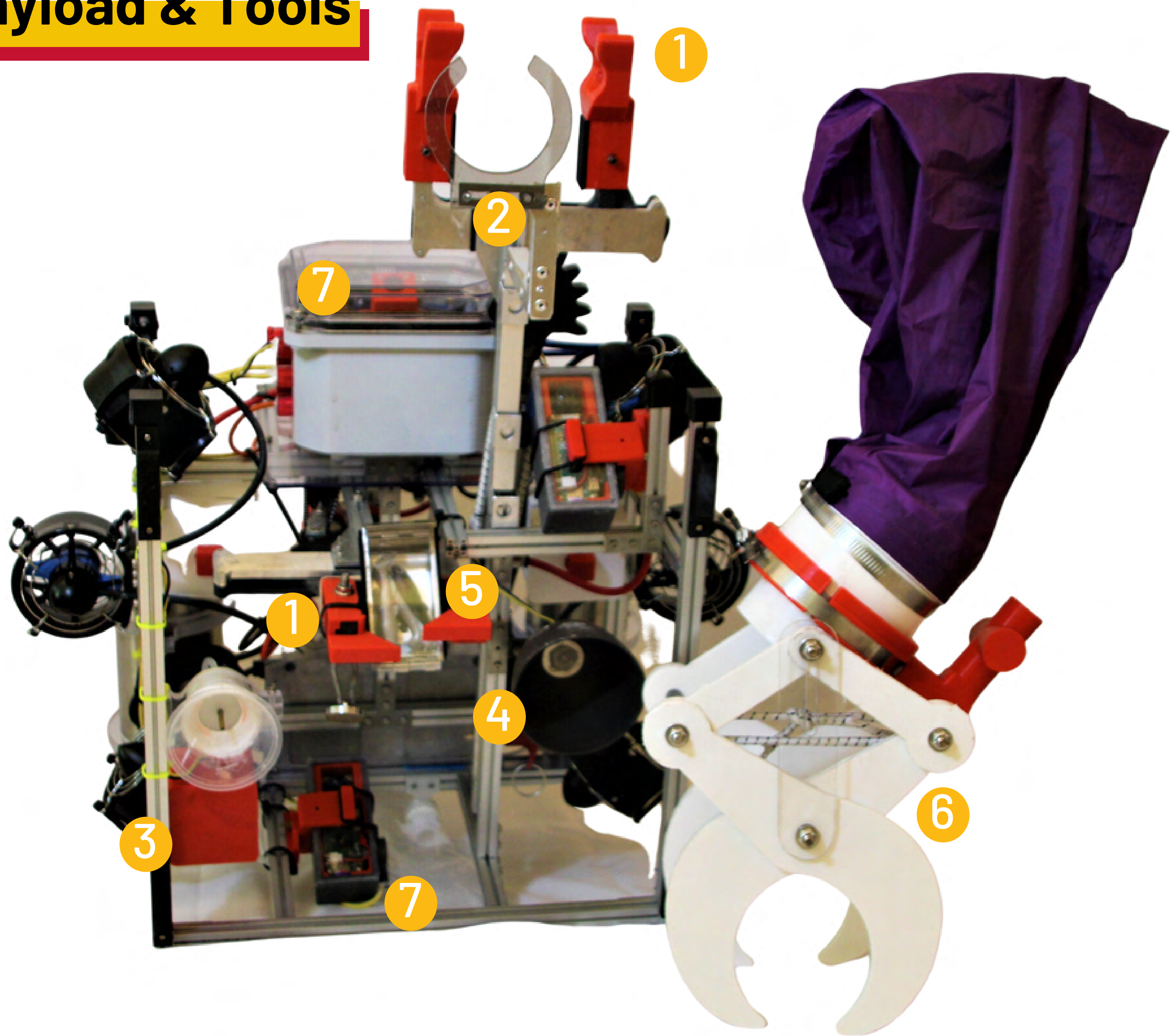


Figure 24. ROV Tools Diagram (Bottom View of ROV)

1. Multipurpose Gripper (Tasks 1.1, 1.2, 2.3, 2.4, 2.5, 2.6, 2.7, 3.1) - Pneumatic actuated parallel grabbing mechanism with interchangeable fingers.
2. Mooring Hook Fingers and U-bolt Brace (Task 1.1) - Interchangeable gripper fingers and integrated alignment brace.
3. Penetrator and Peristaltic Pump (Task 2.2) - Self priming peristaltic pump with sampling cone retrieves an eDNA sample into a sampling bag.
4. UV Light Rx (Task 2.3) - UV light within a light reflector hood to deliver light to a targeted area.
5. Fry Container (Task 2.5) - A container for transportation with a magnetic door release triggered by the ROV.
6. Container Recovery (Task 2.6) - Cylindrical Scissor Lift clamp designed to engage and capture the load. ROV lift capacity is enhanced with a 16 liter lift bag.
7. Wide-angle real time streaming cameras (All Tasks)

The multipurpose gripper was specifically designed with modularity as the primary inspiration. Utilizing quick-release fingers (Figure 25) allows the gripper to be specialized for any task at hand. The same base gripper can be improved upon each year instead of reinvented because the fingers can be easily changed to fit the necessary requirements. The mooring hook fingers demonstrate this by grabbing the mooring hook perfectly and also allowing various other items to be picked up with high-friction foam tape.

Figure 25. Gripper Quick-Release Fingers

The versatile design enables a single manufactured part to fulfill multiple tasks, resulting in cost reduction and improved efficiency for the deck crew.

When developing the container recovery device (Figure 27), inspiration was taken from commonly used pipe-lifting clamps in the industry. Different versions of these clamps have been used previously by ROVOTICS. This process of improving rather than reinventing is commonly used by ROVOTICS to increase the efficiency of designing and manufacturing.

The ROVOTICS eDNA sample collector uses a self-priming peristaltic pump, eliminating the need to remove air from the suction lines, which simplifies the process and makes it more efficient. Since the cost of obtaining a peristaltic pump is relatively low cost, ROVOTICS decided to buy one rather than manufacture it in house. To penetrate the seal,

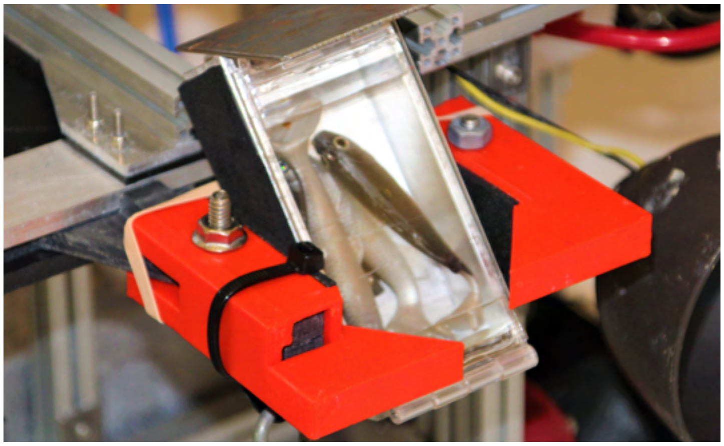


Figure 26. Fry Container in Gripper

ROVOTICS specifically designed a funnel/straw to aid the pilot. For sample storage, ROVOTICS opted for a soft water bottle that surpasses the specified requirements (50 ml of fluid). This design choice mitigates the potential for future issues arising from insufficient fluid collection.

Tardigrade has several onboard ***sensors*** that monitor ROV status. ROVOTICS selected Blue Robotics Bar30 depth sensor, because it has a sufficiently precise resolution, is accurate up to 300m, and to support a MATE sponsor. The ROV's internal leak probes and temperature/pressure sensor report to the Safety Display Panel and are used to ensure the MEH does not flood or overheat. The IMU (Inertial Measurement Unit), which tracks ROV orientation, is used for stabilization in autonomous tasks.

Swordtip Squid (Figure 26) is an autonomous marine device that performs vertical profiles as a part of a Global Ocean Biochemistry Array (GO-BGC). Swordtip communicates the Coordinated Universal Time (UTC) wirelessly to the surface. It consists of two waterproof containers, one housing batteries and the other containing the buoyancy engine. The float can be activated remotely from a mission station, while a real-time clock (RTC) keeps time.

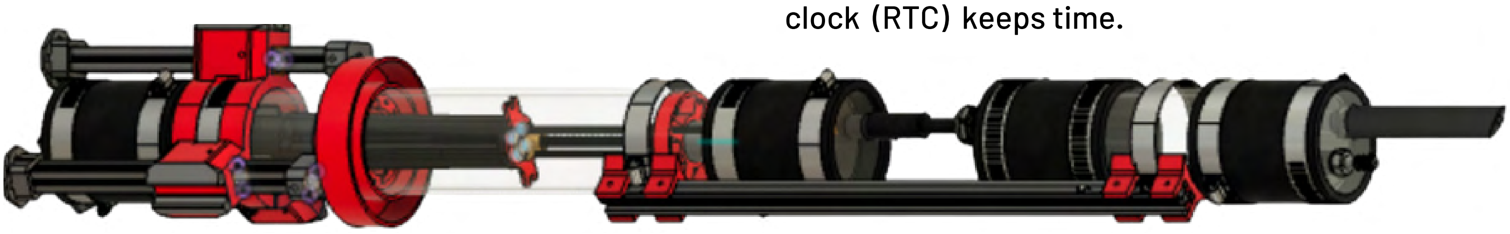


Figure 26. *Swordtip Squid* GO-BGC Float CAD Render

Safety

Ensuring safety is a crucial aspect of ROVOTICS' work, both in building ROVs and in protecting our team members during equipment operations and handling of the ROVs. We understand that the right tools in the hands of competent employees create quality products, but we also realize that improper use of equipment can create serious consequences for operators; Therefore, everyone is required to adhere to operational procedures such as the utilization of safety checklists, personal protective equipment (PPE), and job safety analysis (JSA). Junior employees are required to have a senior member or mentor demonstrate the proper use of any tool, preventing potential harm, while the use of appropriate personal protective equipment is mandatory. All members are responsible for enforcing the use of PPE like safety glasses when operating and maintaining the ROV or working with machinery. One particular risk ROVOTICS has identified is the use of two-part epoxies and the danger they pose to the eyes. Training is required, specific PPE is necessary, and stricter adherence to procedures is used to address this issue. For mission purposes, ROVOTICS has developed scripted communication protocols to enhance further operational safety that allows the deck crew to call the co-pilot to enable or disable tools and systems. Furthermore, the gripper itself is equipped with safety features, including a guard over the gears and padding on the fingers. In addition to protecting employees, these features also keep the environment safe as they carefully handle wildlife and tools. Appendix E contains a safety checklist used in the operation of the ROV.

Critical Analysis

Testing

The ROVOTICS ***vehicle testing methodology*** follows the verification and validation (V&V) methodology. Once a sub-system prototype is designed, it is taken through a verification phase that ensures it can successfully perform its intended task in a simulated environment. Upon integrating the sub-system prototype into the production ROV, the Validation phase is conducted to ensure its effectiveness in completing real-world missions. One example of this methodology in action is the testing of the Lift Bag tool.

The Lift Bag was verified through in-the-pool testing replicating Tardigrade's operational environment. This ensured success upon integration. After thorough verification, the lift bag was integrated into the ROV system, requiring the installation of a bypass valve on the gripper air feed. Due to the substantial air requirement of the heavy lift bag, a final Validation was performed to ensure that its operational use did not compromise the functionality of the gripper and that it successfully fulfilled its mission.

When developing the current generation of gripper fingers, ROVOTICS began by brainstorming several variations that would fit the RFP's criteria. (Figure 29).

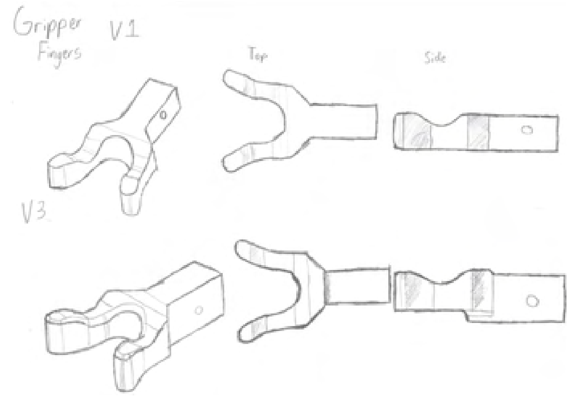


Figure 29. Initial Gripper Finger Design

After several assessments, it was determined that a dual-Y shaped variation that would fit the shape of the mooring connector would work the best. Then, 3D models (Figure 30) were developed using a CAD software to fit the standardized gripper frame design, allowing multiple prototypes to be conceived and compared side by side.

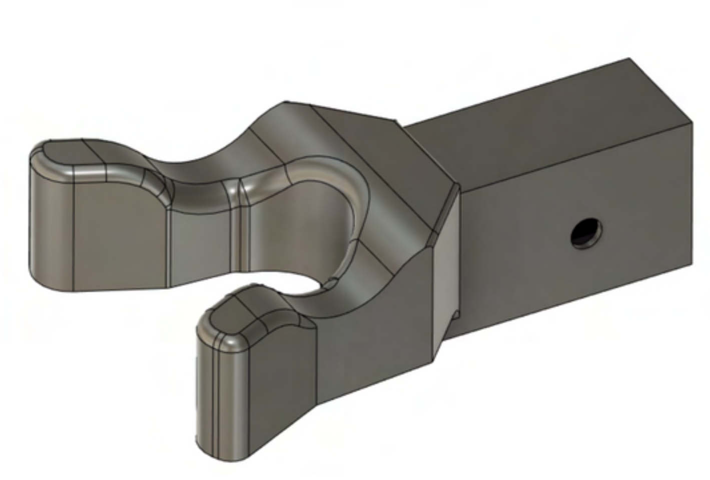


Figure 30. Gripper Finger CAD

3D printed prototypes were manufactured to test the design in a real-world environment. Based on initial testing, several iterations were implemented to improve usability for the pilot. This iterative testing and redesign process repeated until the gripper fingers proved reliable in real-world testing.

Troubleshooting

ROVOTICS employs an iterative troubleshooting process during both the verification and validation phases. The methodology separates the different ROV subsystems, which are then tested independently. This approach allows the identification of the root cause of any issues that arise. Once the root cause is determined, ROVOTICS compares the problem to the specifications to determine the cause or makes necessary adjustments to the specifications to address the issue. This iterative process continues until the final design is successfully validated.

During the validation testing of the ROV, a troubleshooting incident arose when a leak was identified in Tardigrade's Main Electronics Housing. Responding quickly, ROVOTICS initiated its troubleshooting process, which led to the isolation of the problem to a faulty connector. The team carefully managed the task of evacuating water from the housing while ensuring the integrity of the ROV's internal components. Instead of immediately removing the electronics, they opted to conduct an inspection to identify any water droplets present in the higher section of the MEH system near the penetrator. During a thorough examination of the ethernet head, signs of corrosion were observed. This allowed ROVOTICS engineers to successfully diagnose the issue.

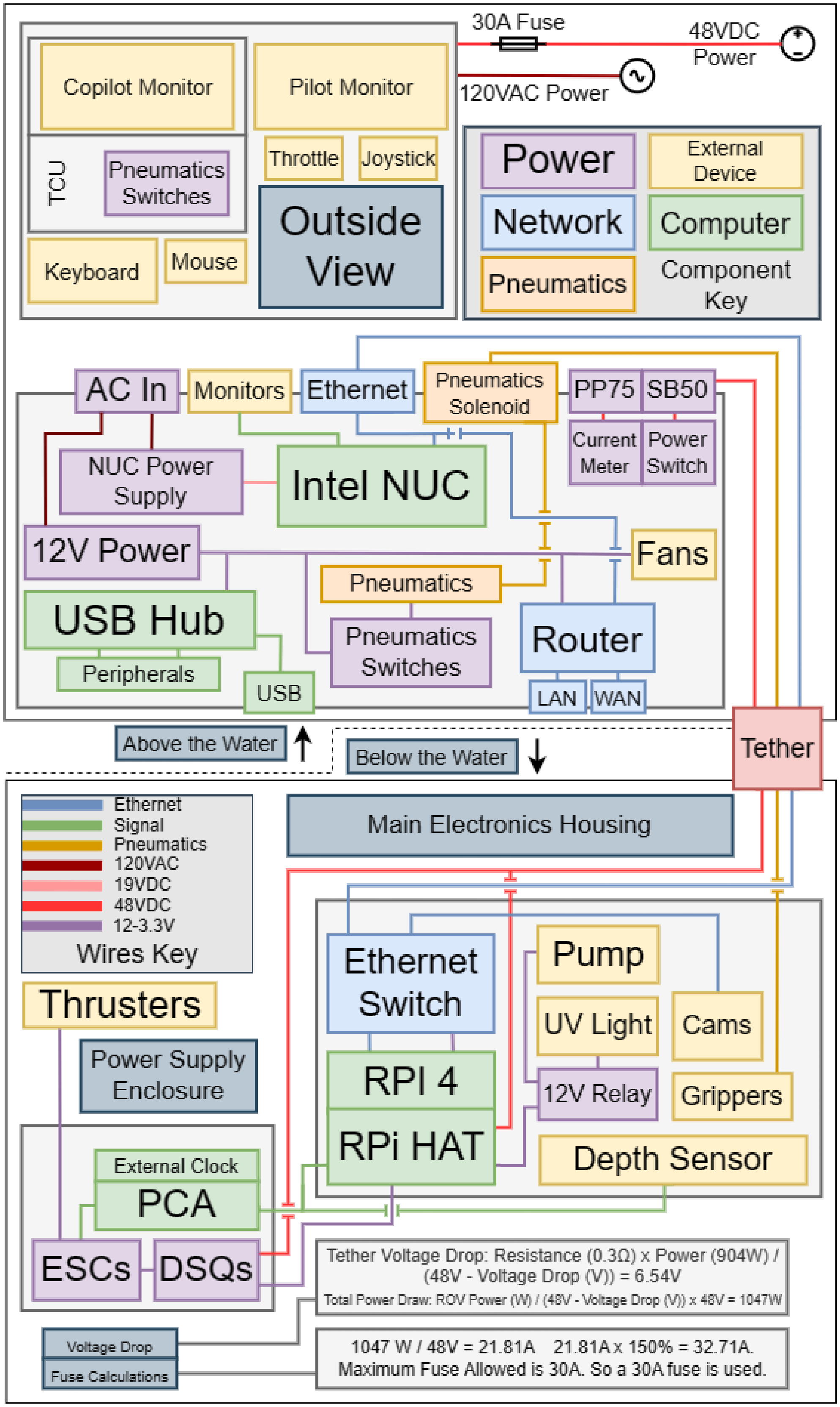
Accounting

ROVOTICS creates a budget at the start of each season (Appendix Item D1), which includes estimated expenses. The budget is determined by considering the actual costs from the previous year. This year, forecasting the budget was much simpler for the company because Tardigrade is built upon a previous ROV base design. By using a standard ROV base design, ROVOTICS could focus on estimating the costs for ROV enhancements and new tools.

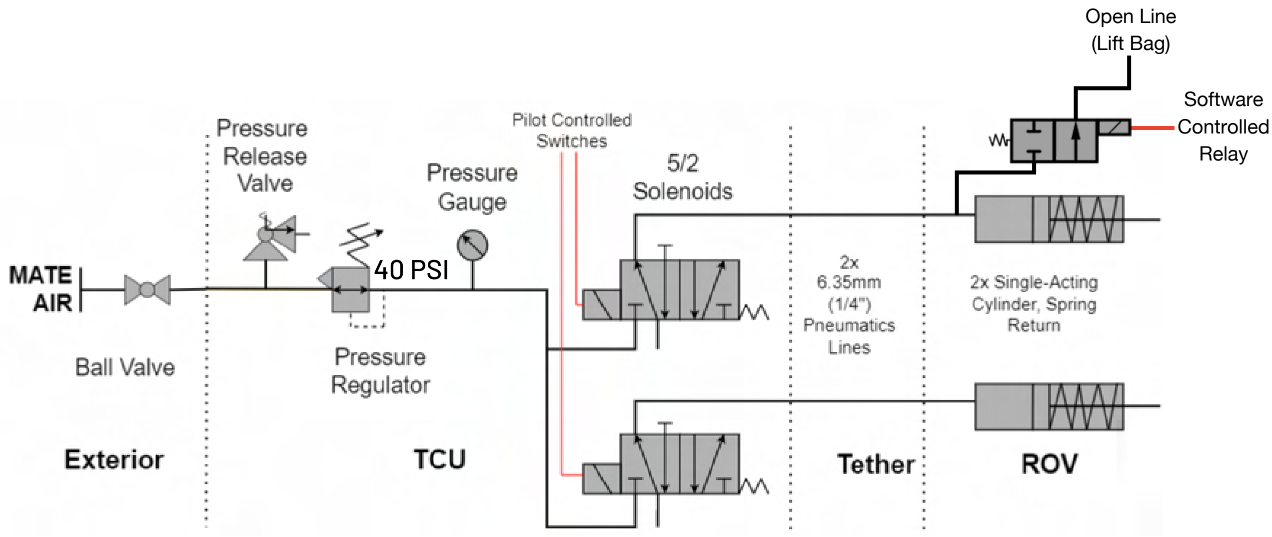
Additionally, expenses related to employee transportation and competition meals are estimated separately. It is worth noting that ROVOTICS employees are responsible for covering these costs.

The estimated income for ROVOTICS is based on funding from Jesuit High School, donations, and employee dues. To ensure that the projected budget is followed, the company submits purchase requests for review and approval by a coach. All purchase receipts are tracked in a project costing sheet, which undergoes monthly review. The 2022-2023 Project Costing report is item D2 in the appendix.

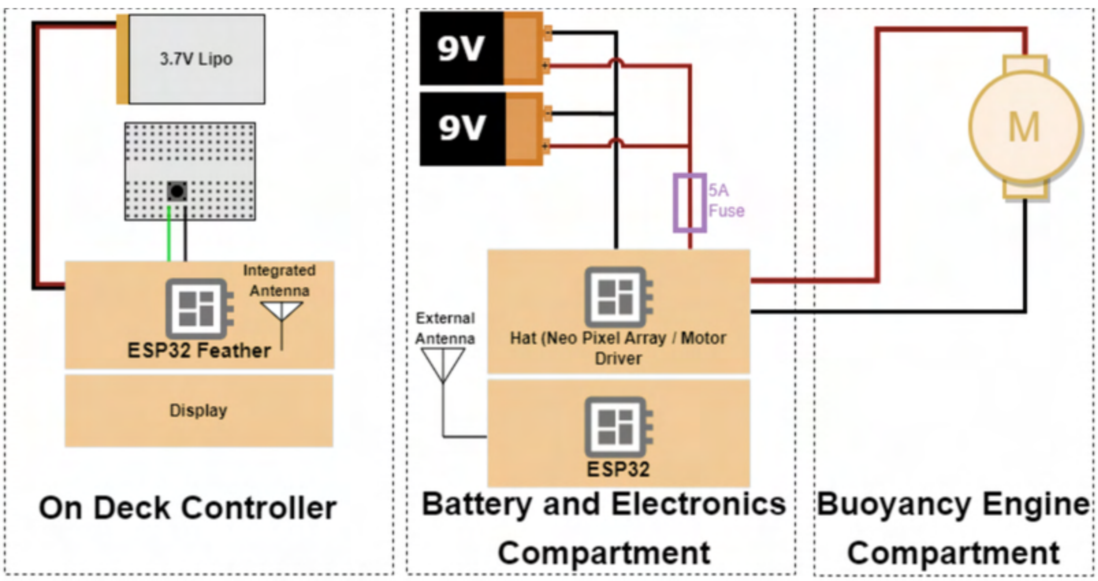
Appendix



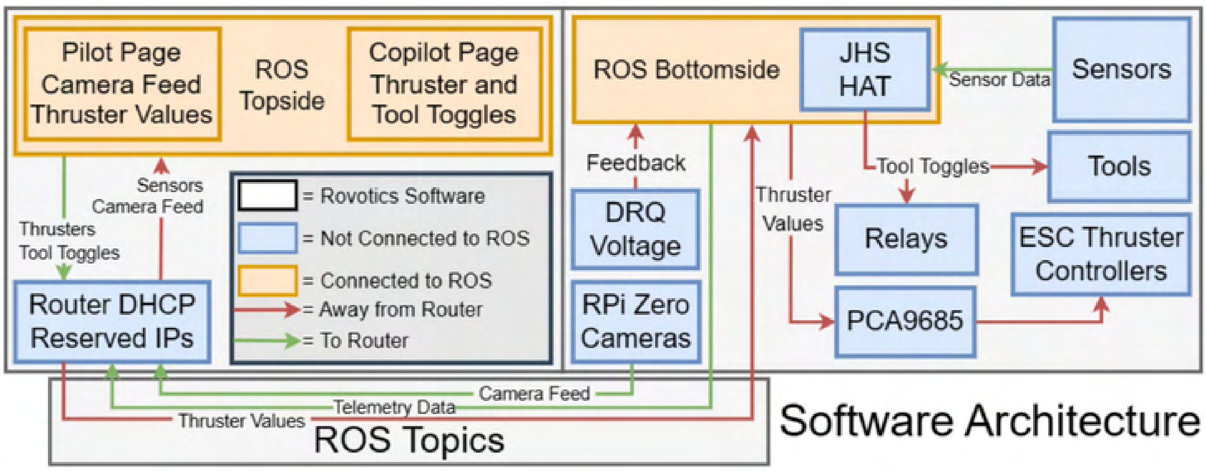
Appendix A1: Electronics SID Diagram



Appendix A2: *Tardigrade*'s Pneumatic SID



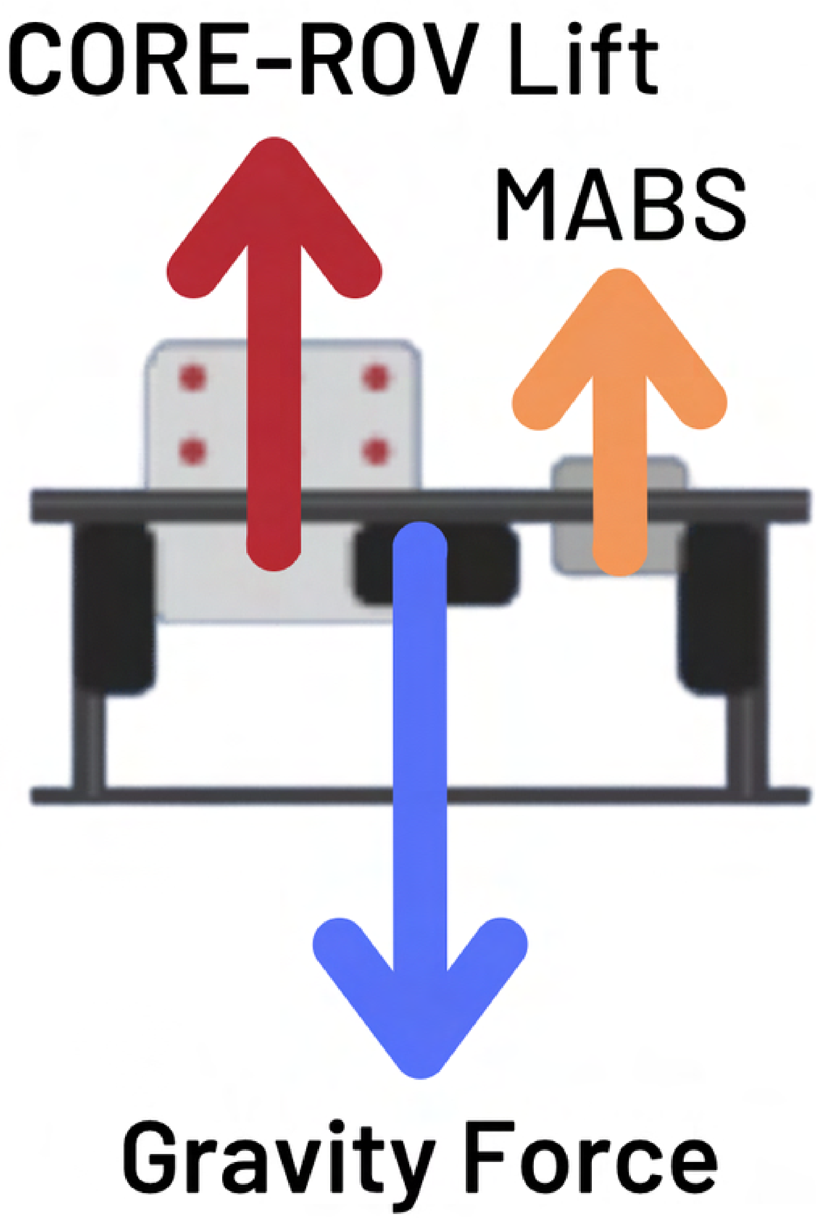
Appendix A3: Float SID



Appendix C: *Tardigrade* Software Architecture

Item	Quantity	Mass (g)	Volume (Cubic cm)	Water Displacement (g)	Net (g)	Net force (Newtons)
Core ROV (electronics enclosures not included)	1	-11700	8601	8601	-3099	-30.4
Static Buoyancy Module	1	-1880	4703	4703	2823	27.69
MAB	2	-6.52	274	274	267.48	2.62
Total:		**-13586.52**		**13578**	**-8.52**	**-0.083**

Appendix B1: *Tardigrade*'s Buoyancy Calculations



Appendix B2: *Tardigrade*'s Free Body Diagram

2022-2023 Project Summary	Item Description	Amount
Income Source		
School Funding	Jesuit School Funding	$ 17,850.00
Donations	MATE Competition Awards	$ 700.00
Available Income		**$ 18,550.00**
Project Cost Summary		
Available Income	School funding & Donations	$ 18,550.00
Actual Project Cost	Production ROV, R&D, Operations Expenses	$ 16,102.53
Project Balance	Budget available for next year	**$ 2,447.47**
Employee Paid Expenses		
Competition Meals	Donations collected for competition meals;14 people	$ 3,521.00
Transporation & hotel subsidy	Donations for car rental, gas, & lodging	$ 1,750.00
Total Employee Paid Expenses		**$ 5,271.00**

Appendix D1: Budget Spreadsheet

2022-2023 Project Cost Summary	Item Description	Type	Budget	Project Cost	Variance
Production ROV Expenses					
Frame & Housing & Bouyancy	Polycase Housings, 15x15 extrusion, foam	Purchased	$ 500.00	$ 527.44	$ (27.44)
Thrusters	(6) T100 Blue Robotics thrusters & ESCs	Purchased	$ 1,200.00	$ 1,076.63	$ 123.38
TCU	Case, Monitors, Electronics, Pneumatics, NUC	Re-used	$ 2,100.00	$ -	$2,100.00
Tether & Connectors	SUBCON, CAT5e wire, strain relief, sheathing	Purchased	$ 450.00	$ 404.06	$ 45.94
Electronics & Connectors	Si wire, connectors, HAT PCB, DSQs, controllers	Purchased	$ 1,500.00	$ 1,293.00	$ 207.00
Pneumatics	Valves, fittings, tubing, gauges	Re-used	$ 100.00	$ -	$ 100.00
Mission Tools	gripper, ROV cameras (8)	Purchased	$ 1,200.00	$ 1,682.63	$ (482.63)
Pilot Controls	Joystick	Re-used	$ 40.00	$ -	$ 40.00
Raw materials	Plastics, metals, hardware, 3D filament, consumables	Purchased	$ 1,500.00	$ 1,770.00	$ (270.00)
Total Production ROV Expenses			**$ 8,590.00**	**$ 6,753.76**	**$1,836.25**
Non ROV Device Expenses					
GO BGC Float	Electronics, plastics, 3D filament, batteries, wire	Purchased	$ 600.00	$ 757.12	$ (157.12)
Total non ROV Device Expenses			**$ 600.00**	**$ 757.12**	**$ (157.12)**
R&D Expenses					
3 SW Test Benches	Test Bench materials	Re-used	$ -	$ -	$ -
1 Electronics Test Bench	Test Bench materials	Purchased	$ 250.00	$ 236.75	$ 13.25
Total R&D Expenses			**$ 250.00**	**$ 236.75**	**$ 13.25**
Operations Expenses					
Lodging	7 hotel rooms for team/2 per room @ 5 nights	Purchased	$ 6,700.00	$ 5,787.25	$ 912.75
Mission Props	MATE mission props	Purchased	$ 500.00	$ 349.11	$ 150.89
MATE Entry Fee	MATE entry fee	Purchased	$ 425.00	$ 450.00	$ (25.00)
Power Fluid Quiz Fee	MATE power fluid quiz	Purchased	$ 25.00	$ 25.00	$ -
Lab Supplies	Lab Supplies: Consumables, plastic, glue, hand tools	Purchased	$ 475.00	$ 650.00	$ (175.00)
ROV shipping	Freight shipping from California to Colorado	Purchased	$ 3,000.00	$ 1,600.00	$1,400.00
Printing	Report, display, brochure printing	Purchased	$ 300.00	$ 250.67	$ 49.33
Total Operations Expenses			**$ 11,425.00**	**$ 9,112.03**	**$2,312.97**
Total Project Variance			**$ 20,265.00**	**$ 16,102.53**	**$4,162.47**

Appendix D2: Project Costing Spreadsheet

Pre-Power Procedure (Pilots & Deck Crew)

- ☐ Area clear and safe (no tripping hazards, items in the way)
- ☐ Verify power switches and circuit breakers on TCU are off
- ☐ Tether flaked out on the deck and free from damage
- ☐ Tether connected to TCU and secured
- ☐ Tether connected and secured to ROV
- ☐ Tether strain relief connected to ROV
- ☐ Verify the electronics housing sealed
- ☐ Visually inspect electronics for damaged wires, loose connections
- ☐ Fasteners are tight on the electronics housing
- ☐ Thrusters free from obstructions
- ☐ Power source connected to TCU
- ☐ Vacuum test electronics housing (see vacuum test procedure)
- ☐ Verify vacuum check port is securely capped

Vacuum Test Procedure (Deck Crew)

- ☐ Verify MEH housing fasteners are secure and visually inspect front cover seal.
- ☐ Verify PSE screws are secure.
- ☐ Verify screw caps on all cameras are secure
- ☐ Connect vacuum hand pump to ROV electronics housing
- ☐ Pump electronics housing to -35 kPa (vacuum), this is 10 inches of Hg on the gage.
- ☐ Verify electronics chamber holds -35 kPa (vacuum) for 5 minutes
- ☐ Remove vacuum pump and securely cap vacuum check port
- ☐ Stow vacuum hand pump back in case

Power Up Procedure (Pilots & Deck Crew)

- ☐ Verify TCU receiving 48V 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)
- ☐ Switch between each camera to verify video feeds and proper camera positioning.
- ☐ Test any electrical or pneumatic tools that require pilot control

Launch Procedure (Pilots & Deck Crew)

- ☐ Place ROV in water
- ☐ Visually check for bubbles
- ☐ If there are bubbles from the electronic housings, remove ROV from water immediately and call out "electronics leak". Proceed with Leak Detection Protocol
- ☐ The deck crew calls out "Ready to Launch"
- ☐ Deck crew members handling ROV call out "Hands Off!"
- ☐ Co-pilot calls out "Thrusters Engaged" and pilot begins mission

ROV Retrieval (Pilots & Deck Crew)

- ☐ Pilot calls "ROV Surfacing"
- ☐ The deck crew calls out "ROV Surfaced. Disable thrusters"
- ☐ Co-Pilot disables thrusters and calls out "Thrusters disabled"
- ☐ The deck crew calls "Hands On", and removes ROV from the water
- ☐ After securing the ROV on deck, the deck crew calls out "ROV Secured on Deck"
- ☐ Co-Pilot powers down TCU if the team is demobilizing from deck.

Leak Detection Protocol (Pilots & Deck Crew)

- ☐ Power down system and remove ROV from water if running a mission. Recover ROV by pulling to the surface using the tether if required.
- ☐ Visually Inspect to determine source of leak. Do not disassemble any part of the ROV until the leak is located.
- ☐ Install pressure testing equipment and use soapy water to verify the leak source.
- ☐ Create a plan to repair the leak and check all systems for damage and proper operation.
- ☐ Document the cause of the leak and implement corrective action or design changes as required

Loss of Communication (Pilots & Deck Crew)

- ☐ 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
- ☐ If communication is not restored, begin troubleshooting procedures, Isolate the issue. Is there a hardware or software cause? Proceed to analyze/ isolate cause
- ☐ Document the cause of the failure and implement corrective action or repair as required

Pit Maintenance (All Team Members)

- ☐ Pit is organized and free of garbage.
- ☐ Verify all tools and cables are neatly stored and there are no trip hazards.
- ☐ Check electrical cords and correct any possible electrical hazards
- ☐ Clean Thrusters with Deionized Water
- ☐ Inspect Tether Power and Network Connectors
- ☐ Check supplies and organize a shopping list if anything is needed for repair or upkeep.
- ☐ Verify TCU, ROV and tether are clean, dry and properly stored. Protective caps for electrical connectors should be in place
- ☐ ROV, TCU and tether have been readied for use on the next mission run

Inspect and Test Pneumatics (Pilots & Deck Crew)

- ☐ Verify all pneumatics lines are properly connected to the air source, TCU, and ROV
- ☐ Verify that the compressor is switched on
- ☐ Activate pneumatics system and open main valve
- ☐ Verify there are no leaks and pneumatic lines are securely connected while under pressure
- ☐ Test tools and adjust pressure regulator to 2.75 Bar (40PSI)

Appendix E: ROV Operations Safety Checklist